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Original Research Article

Effects of cropland abandonment and afforestation on soil redistribution in a small Mediterranean mountain catchment

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ABSTRACT

In slopes of Mediterranean mid-mountain areas, land use and land cover changes linked to the abandonment of cropland activity affect soil quality and degradation and soil redistribution; however, limited attention has been paid to this issue at catchment scale. This paper evaluates the effects of cropland abandonment and post-land abandonment management (through natural revegetation and afforestation) on soil redistribution rates using fallout ^{137}Cs measurements in the Araguás catchment (0.45 km^2, Central Spanish Pyrenees). A total of 52 soil core samples, distributed in a regular grid, from the first 30–40 cm and 9 sectioned reference samples were collected across the catchment and soil properties were analysed. Fallout ^{137}Cs was measured in a 5 cm sectioned references samples and in bulk grid samples. ^{137}Cs inventories were used to estimate soil erosion and deposition rates across the catchment. Results show that the highest erosion rates were recorded under sparsely vegetated sites in the badland area, while the lowest rates were found in the afforested area, but no significant differences were observed between the different uses and covers in soil redistribution rates likely due to a long history of human intervention through cultivation in steep slopes and afforestation practices. However, the recovery of the soil organic matter in afforested areas suggest that afforestation can reduce soil degradation at long-term scale. The information gained achieve a better understanding of soil redistribution dynamics and provide knowledge for effective land management after cropland abandonment of agroecosystems in Mediterranean mountain areas.

1. Introduction

Mediterranean mid-mountain areas are sensitive agro-ecosystems prone to land degradation (García-Ruiz et al., 2013). Land use and land cover changes (LULCC) have been a continuous feature in these areas since the beginning of human civilization (García-Ruiz, 2010). Mountain slopes were cultivated with cereal crops, even on steep slopes, stony soils and under extreme climate conditions (Lasanta et al., 2020). However, during the second half of the 20th century, the farming systems in the Mediterranean mountains were progressively abandoned and a forest cover subsequently re-expanded through natural revegetation processes (passive restoration) or afforestation (active restoration) (García-Ruiz et al., 2020). LULCC have been identified as major drivers of Global Change due to their impact on ecosystem services, such as water resources and soil degradation. In addition, there is an overall agreement that LULCC and climate change will be rapid and strong in Mediterranean mid-mountain areas (García-Ruiz et al., 2011; Lionello & Scarascia, 2018).

Natural revegetation processes and afforestation after cropland abandonment are different strategies to restore soil ecosystem services, such as nutrients, soil conservation and carbon sequestration (Bell et al., 2020). In general, natural revegetation after land

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abandonment results in a decline in water resources (Khorchani et al., 2020; Peña-Angulo et al., 2021; Vicente-Serrano et al., 2021), a decrease in soil loss and sediment delivery (García-Ruiz & Lana-Renault, 2011; Nadal-Romero et al., 2013), as well as changes in the connectivity between sediment sources and channels (Foerster et al., 2014; Francke et al., 2018; Lana-Renault et al., 2018; Llena et al., 2019).

Afforestation has been increasingly implemented around the world, and extensive afforestation programs were conducted by national forest services all over the Mediterranean region (i.e. Yaşar Korkanç, 2014). In Spain, during the first half of the 20th century, afforestation plans were adopted to meet a number of socioeconomic and environmental needs, such as creating employment and diversifying rural incomes, generating prime materials for paper industry, controlling the hydrological and geomorphological processes (particularly in the degraded areas due to past agricultural activities), and preventing flooding and reducing check dam siltation (Ortigosa et al., 1990). In the Spanish Pyrenees, as in most Mediterranean mid-mountains, afforestation has been mainly based on several pine species. Pines (adapted to the ecological conditions of Mediterranean mid-mountain areas) are fast growing trees and likely lead to a quick soil hydrologic restoration and the formation of a protective vegetation cover, although still a scientific debate exists related to the benefits of afforestation in Mediterranean mountain areas (i.e. Nadal-Romero et al., 2016a). In that sense, there is evidence that afforestation not only alters aboveground vegetation, but also leads to significant changes in soil properties, as well as in soil conservation and soil erosion (Nadal-Romero et al., 2016a; Romero-Díaz et al., 2010). Likewise, afforestation also reduces water yields and soil loss (Andréassian, 2004; Khorchani et al., 2021; Scorpio & Piégay, 2021), and modifies the connectivity between sediment sources and channels (Sanjuan et al., 2016).

Mediterranean soils are considered the most fragile part of the ecosystem due to the low organic matter content and the low rate formation, with thin and poorly developed soils (García-Ruiz et al., 2013). Thus, the impact of land degradation and soil erosion processes on Mediterranean ecosystems has received increasing attention during the last decades (Bell et al., 2021; Gaspar et al., 2021; Lizaga et al., 2019; Quijano et al., 2016; Romero-Díaz et al., 2017). Since vegetation recovery differs from natural revegetation to afforestation, soil conservation is expected to be different under these contrasting scenarios of passive and active restoration.

To understand land degradation processes, soil redistribution processes need to be quantified to assess how LULCC and post-land abandoned practices affect soil loss in Mediterranean mid-mountain areas. Different methodologies have been used to estimate erosion rates worldwide (García-Ruiz et al., 2015), but few studies have used caesium-137 (^{137}Cs) to estimate and quantify soil erosion rates and soil redistribution at catchment scale (i.e., Porto et al., 2003; Lizaga et al., 2018, 2019), and only some examples have been published investigating the effects of land abandonment and post-land abandoned practices (passive and active restoration) on soil erosion using the proposed approach (i.e. Evrard et al., 2010; Navas et al., 2017). Different studies have discussed about the uncertainty and usefulness of ^{137}Cs as a tracer for soil erosion assessment (i.e. Boardman, 2006). Parsons and Foster (2011) challenged the usefulness of this radioisotopic method primarily by questioning the assumption of the representativeness of the reference inventory and its conservative behavior and the ^{137}Cs data conversion into soil erosion rates. However, Mabit et al. (2013) agreed that the applicability of the ^{137}Cs method to assess soil erosion magnitude needs careful planning, as well as expert knowledge, but highlighted that if the method is based on suitable and statistically sound sampling, ^{137}Cs is a very effective soil tracer to assess the magnitude of soil erosion.

Since the first application of fallout ^{137}Cs in Mediterranean mountains (Navas & Walling, 1992), LULCC was identified as a main factor of soil mobilisation driving the source to sink paths of sediments (Quine et al., 1994). The role of rapid LULCC triggered by cropland abandonment on soil redistribution was first assessed at catchment scale using a transect based on ^{137}Cs approach (Navas et al., 2005), and detailed information of ^{137}Cs profiles allowed to interpret changes in soil properties and on the lateral transfer of soil and nutrients (Gaspar et al., 2019). Later, the potential of grid setups of ^{137}Cs measurements provided fundamental data to address the spatial patterns of soil redistribution and that of associated nutrients in catchments with dynamic LULCC after cropland abandonment (Gaspar et al., 2021; Navas et al., 2011). Grid ^{137}Cs estimates in complex catchments with intricate mosaic of land use and land covers (LULC) permitted the identification of which of them acted as sinks or sources of soil particles and soil dynamics (Navas et al., 2014). Due to the magnitude of LULCC affecting Mediterranean mountain agroecosystems, further insights on the effect of such changes was assessed in medium size catchments by Lizaga et al. (2018), where ^{137}Cs derived soil redistribution was linked to afforestation, revegetation processes and agricultural practices with clear impacts on soil properties after cropland abandonment (Lizaga et al., 2019).

The main objective of this study is to assess the effects of cropland abandonment and post-land abandonment management (through natural revegetation and afforestation) on soil redistribution rates using fallout ^{137}Cs measurements at catchment scale (Araguás catchment, Central Pyrenees). The specific objectives are to (i) establish the reference inventories of ^{137}Cs in soils of representative undisturbed Mediterranean vegetation cover, and (ii) compare the estimated reference inventory with the grid sampling inventories to identify areas of ^{137}Cs loss or gain in the catchment related to LULCC and afforestation practices.

We start from the following research hypotheses: LULCC after cropland abandonment and post-land abandonment practices have a significant impact on soil redistribution rates, and afforestation can reduce soil degradation after cropland abandonment compared to natural revegetation.

Previous studies have been carried out in the Araguás catchment related to hydrological dynamics (Nadal-Romero et al., 2018), erosion processes (Nadal-Romero et al., 2015) and the effects of afforestation and land use changes on soil properties and SOC dynamics (Nadal-Romero et al., 2016a; 2016b). However, in the Araguás catchment, a representative catchment of LULCC in Mediterranean mountain areas, no information has been published so far, on the effects of LULCC and post-land abandonment management at catchment scale (through natural revegetation and afforestation) on soil redistribution, or the use of fallout ^{137}Cs to estimate soil redistribution rates.

2. Materials and methods

2.1. The Araguás catchment

The Araguás catchment (0.45 km^2) is a north-south small instrumentalized catchment, with altitudes between 780 and 1100 m a.s.l. (Fig. 1A, B, 1C). The present landscape is a complex mosaic in which alternate: (i) afforested areas, that were previously cultivated with cereal crops in terraced fields and were afforested in the late 1960s with Black pine (*P. nigra*) and Scots pine (*P. sylvestris*) (Fig. 1D), (ii) dense and open shrub areas that were also cultivated and underwent a process of natural plant colonization (natural revegetation) with *Genista scorpius*, *Juniperus communis*, *Rosa gr. Canina* and *Buxus sempervirens* (Fig. 1E), (iii) small agricultural areas characterized by permanent pasturelands for

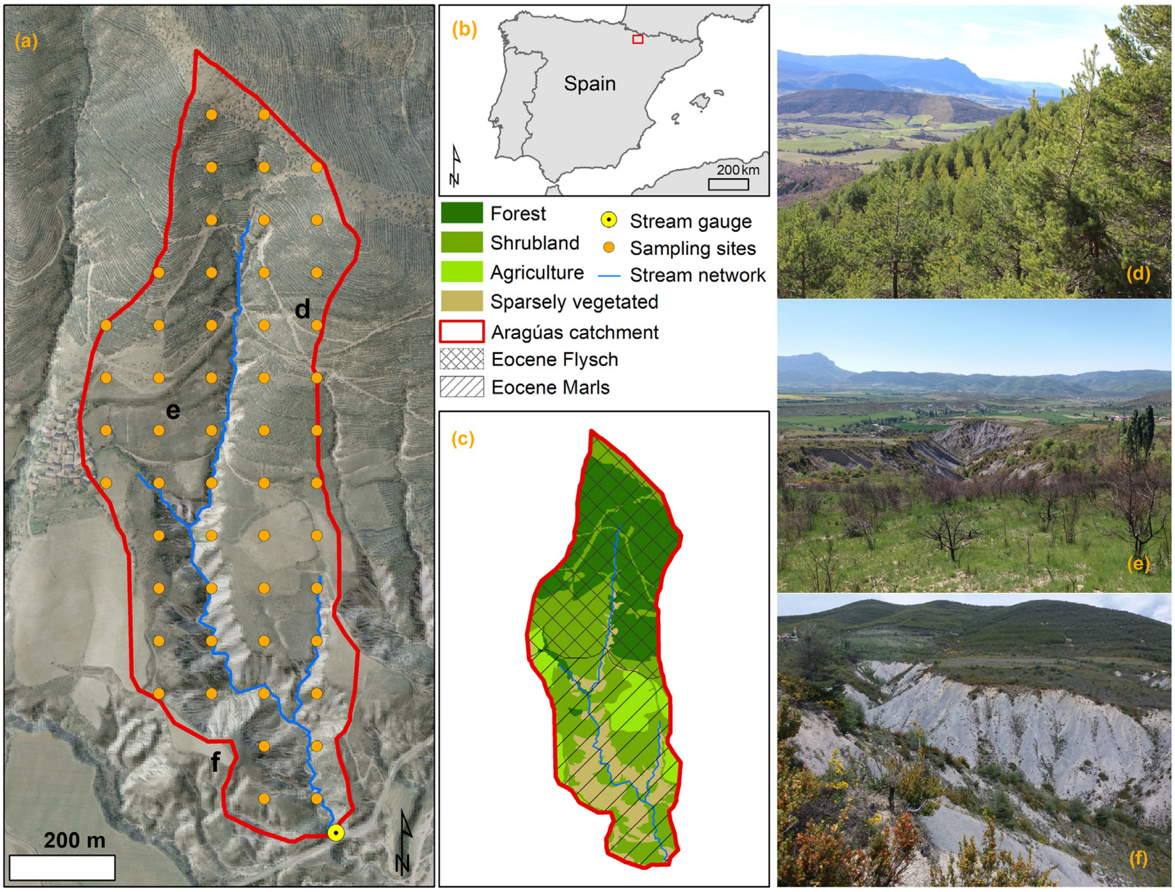


Fig. 1. The Araguás catchment. (a) The sampling network composed by a grid of 100 * 100 m; (b) location of the catchment in Spain; (c) land cover map using the aerial photography PNOA 2018; (d) afforestation in the upper part of the catchment; (e) natural revegetation in the abandoned croplands; (f) eroded marls around the main stream and pasturelands in the upper part of the slopes. Black letters in Plot (a) indicate the location of a, e, and f.

grazing but not currently tilled (Fig. 1E), and (iv) badlands characterized by sparse vegetation cover and extreme geomorphological dynamics (Fig. 1F). Sparsely vegetated areas showed the highest slope gradient (52.95%); the average slope gradient in afforested sites was 42.20%, in shrublands 37.71% and in grasslands 21.04%.

Two different lithologies are present in the catchment (Fig. 1C): Eocene marls and Eocene turbidites (Flysch formation consisting of bedded thin layers of sandstones and marls), in the lower and upper part of the catchment, respectively. Badland areas developed mainly the Eocene marls, while afforested sites are developed in the upper part of the catchment (Flysch formation). The soils are stony and shallow, resulting from decades of cultivation, and are classified as Calcaric Leptic Regosols following the WRB taxonomy (IUSS Working Group WRB, 2015).

Climate in the area is sub-Mediterranean with oceanic and continental influences and mean annual temperature is 10 °C (ranging between −15 °C and >30 °C) and mean annual precipitation is 800 mm (oscillating between 500 and 1000 mm).

2.2. Soil sampling design

In 2019 a total of 52 bulk core soil samples were collected (Fig. 1A). A steel core tube was used to obtain two replicates of bulk soil samples at each sampling point from the surface until a depth varying from 30 to 40 cm depending on the local soil thickness. In the badland areas, we avoided sampling steep slopes where soils are likely to be totally eroded and selected proximate sparsely vegetated areas. The sampling points were distributed proportionally across the catchment surface using a 100 × 100 m grid with a sampling density of 1.2 sample ha^{-1} (see Fig. 1A). The selection of the grid sampling scheme was carried out to obtain a regular distribution of the sampling sites over the catchment and the land uses. We tested several sampling densities, however the selected sampling grid fitted the best with our study area and the economic resources available for laboratory analysis.

In order to establish the local reference inventory for the instrumentalized catchment, nine core samples were collected as reference sites in flat undisturbed locations under stable soil conditions, where neither erosion or deposition was expected to have occurred during the last decades. Sampling was done using core tubes on a depth varying from 40 to 45 cm. The soil cores were sectioned in 5 cm intervals in order to study the vertical distribution of ^{137}Cs (see Fig. 2).

2.3. Soil analysis

The two soil cores from each sampling site were opened and air-dried in the laboratory then mixed, homogenized and sieved to ≤2 mm. Soil properties were determined in the laboratory at the Pyrenean Institute of Ecology (IPE-CSIC) and at the Experimental Station of Aula Dei (EEAD-CSIC): (i) particle size analysis was carried out with a Beckman Coulter LS 13 320 laser diffraction particle size analyser (Beckman Coulter Inc., 2011) after oxidizing the organic matter by pre-treating the soil with H_2O_2 (10%) in a boiling

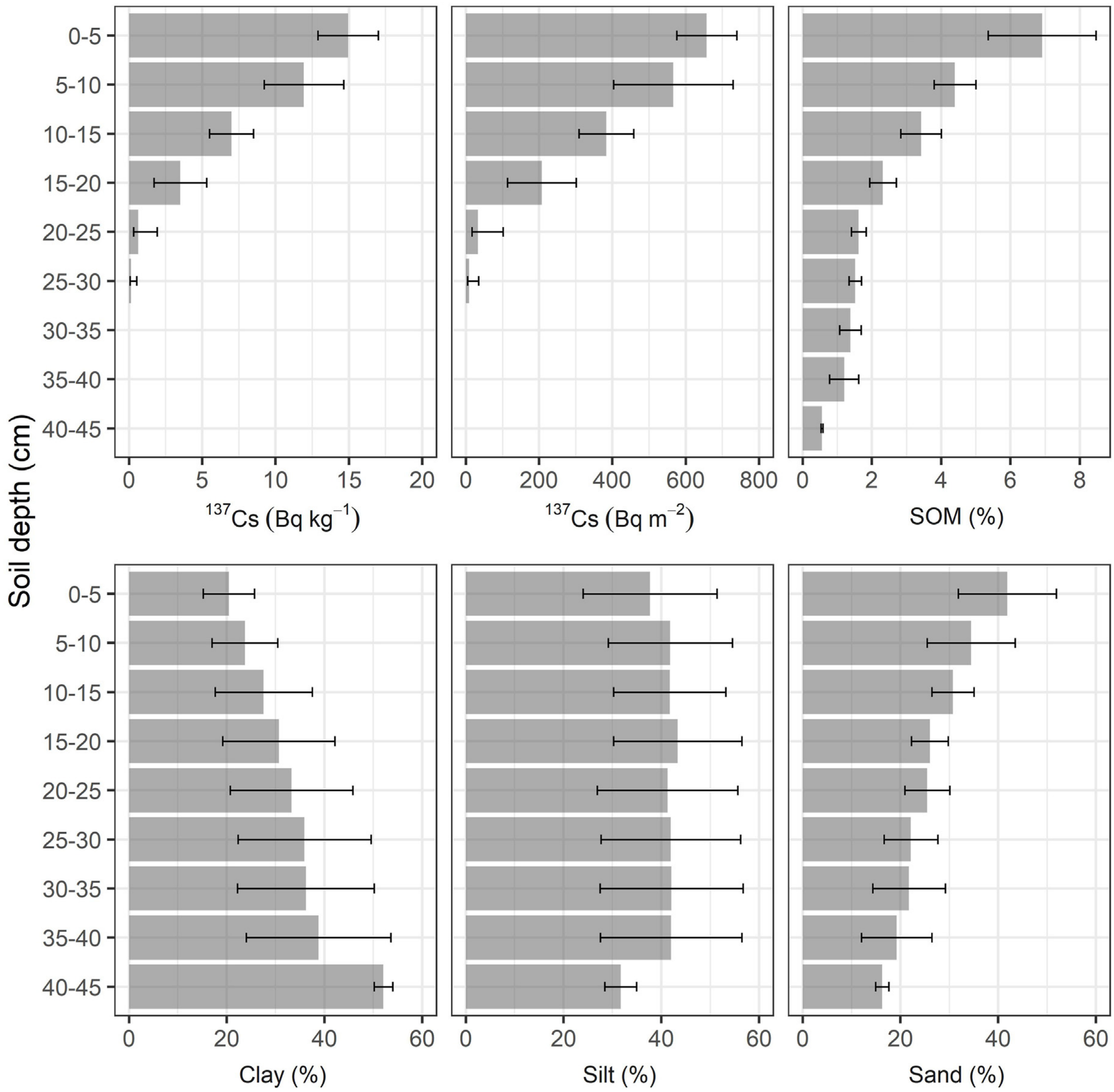


Fig. 2. Depth distribution of the mean ^{137}Cs activity and inventories, soil organic matter (SOM), soil texture (clay, silt and sand contents) in the reference profiles (n = 9). Error bars represent the standard deviation.

water bath at 80 °C and adding 2 ml of solution of a dispersing agent (40% sodium hexametaphosphate to avoid grain flocculation) (Murray, 2002); and (ii) Total carbon and soil organic carbon were measured by dry combustion in an elemental analyser (LECO CNS 928, Leco Corporation) and soil organic matter (SOM) was calculated using the van Bemmelen factor assuming that organic matter contains 58% organic carbon.

The methodology followed for ^{137}Cs analysis has been widely described in the literature (i.e. Walling & Quine, 1991; Navas & Walling, 1992; Navas et al., 2005, 2008, 2011; among others). Measurements of ^{137}Cs mass activity were performed using a high resolution, hyperpure germanium, coaxial gamma-ray detector (50% efficiency) of the Experimental Station of Aula Dei (EEAD-CSIC, Spain) coupled to an amplifier and multichannel analyser (Canberra Xtra, Canberra industries, Inc. USA). The content of ^{137}Cs was expressed as a concentration or massic activity (Bq kg^{-1}). Estimates of soil redistribution rates (Mg ha^{-1} yr^{-1}) derived from ^{137}Cs inventories (Bq m^{-2}) were obtained by applying the conversion model reported by Soto and Navas (2004, 2008) for uncultivated and cultivated soils. These models compare the measured inventory with the local reference inventory and determine the erosion or deposition rates relative to the reference inventory.

2.4. Data analysis

As the assumption of normal distribution per factor when checked by the Shapiro Wilk normality test was met for most parameters, parametric tests were used to monitor differences between LULC and soil redistribution. The homogeneity of variance using Levene's test was also carried out. R. Pearson's correlation coefficients were used to assess the relationships between soil properties and ^{137}Cs values. A one-way analysis of variance (ANOVA) and the Tukey Post-Hoc tests (when the F test was significant) were performed to assess differences between LULC and to evaluate if erosion and deposition rates were different in function of land uses. In all cases, we considered differences to be statistically significant at $p < 0.05$.

In addition, a Principal Component Analysis (PCA) was performed to analyse the relationships between ^{137}Cs and clay, silt, sand, SOM contents and discriminate differences between LULC.

The sampling adequacy of variables was analysed by the Kaiser-Meyer-Olking measure (>0.50) and by Bartlett's test of sphericity (<0.005). The selection of the main components was based on the latent root criterion with eigen-values > 1.0. All statistical analyses were carried out using R 3.4.3.

Finally, an ordinary kriging with constant trend and stable semivariogram was used to model the spatial distribution of the analysed variables at catchment scale. All the output maps and interpolations were performed using ESRI ArcGis software.

3. Results

3.1. Soil properties in the reference sites

Fig. 2 shows the clay, silt, sand and SOM contents at the nine reference sites. In general, soils in the undisturbed areas were shallow and poorly developed. Coarse fraction was homogeneously distributed through the soil profile. Most soil samples had a clay (34% of the samples) and silt loam (32% of the samples) texture, with silt fraction predominating in all depths (except >40 cm). The mean values of clay, silt, and sand were 31.4 ± 13%, 41.2 ± 13%, and 27.4 ± 10% respectively. The mean SOM content in reference 5 cm intervals was 1.6%. Around 80% of the ^{137}Cs massic activity values were below 10 Bq kg^{-1}. The reference ^{137}Cs inventory for the Araguás catchment was 1854.0 ± 101 Bq m^{-2}, and varied between 1641.2 and 2009.8 Bq m^{-2}.

The reference profiles showed an exponential decrease of ^{137}Cs, SOM and sand, from the surface to the deepest layers (Fig. 2). Clay fraction showed a slight increase with depth, while silt content was distributed relatively uniform with depth, and had no significant differences between the top and deep soil layers. ^{137}Cs massic activity was undetectable below 30 cm (Fig. 2).

3.2. Soil properties in the Araguás catchment

^{137}Cs mass activity in the catchment ranged from below detection limit to 7.1 Bq kg^{-1} (only 14% of the samples had a massic activity higher than 5 Bq kg^{-1}) (Fig. 3); and the inventories of ^{137}Cs varied from 0 to 2915.6 Bq m^{-2} (Table 1 and Fig. 3).

All the samples from the catchment had a silt-loam texture with a mean value of 67% of silt content, ranging between 57 and 76% (Fig. 3). Mean sand and clay contents were 14% and 19% respectively. SOM values oscillated between 0.7 and 3.5%, with a mean value of 1.9% (Table 1).

Significant differences were found between LULC (Fig. 3). Silt and clay values were significantly lower in the afforested areas (Table 2). Significant differences were also observed related to silt content between shrubs and agricultural areas and sparsely vegetated areas. SOM and sand values were higher in the afforested areas compared to shrubs and sparsely vegetated areas. In these afforested areas, ^{137}Cs mass activity (excluding points below detection limit) (see Fig. 1 Supplementary material) was higher than in shrubs and sparsely vegetated areas. No differences were observed between LULC related to ^{137}Cs inventories (Figs. 3 and 1 Supplementary material and Table 2).

Fig. 4 shows the spatial distribution of the interpolated soil properties and ^{137}Cs mass activity and inventory. In general, the soil properties were highly variable across the catchment, and the spatial pattern was not so clear for most of the properties (see Fig. 4). Relatively high clay and silt contents were recorded in the lower part of the catchment. No differences related to lithology were observed for SOM and ^{137}Cs mass activity and inventory. High SOM values were found at the upper part of the catchment, related to the presence of the afforested areas (Table 2), whereas lower values were found in the lower part of the catchment, close to the ravine, related to the presence of sparsely vegetated areas and badlands (Fig. 4). High ^{137}Cs mass activity and inventory values were found in the upper part of the catchment and related to some agricultural areas.

Fig. 5 shows the correlation between soil properties considering all the LULC. ^{137}Cs activity and inventory were directly and significantly correlated with SOM and sand contents, and inversely correlated with silt contents. No significant correlations were found between ^{137}Cs activity and inventory and clay contents. SOM content was directly correlated with sand, and inversely correlated with silt.

Fig. 6 shows the results of the PCA analysis and the PCA scores in the plane of PC1 and PC2. On the first component, values were large and positive for SOM and sand, and large and negative for silt, which explain 57.8% of the variance. The second component explained 23.2% of the variance and showed large and positive eigenvector values for ^{137}Cs activity and inventory and clay content. Although no strong discrimination was evident, there were some differences between LULC. Afforested sites were on the positive side of PC1, clearly separated from sparsely vegetated sites, and with large values of SOM and sand. The sites of agricultural use and shrubs were clustered together close to the centre of both components. Sparsely vegetated sites were partially distinguishable, on the negative side of both components with high silt values, and low values of SOM contents.

3.3. The effects of soil redistribution on soil properties

The sampling sites were classified into three categories: deposition, erosion and stable sites. Compared to the reference inventory (1854 ± 101 Bq m^{-2}), higher ^{137}Cs inventories were considered as deposition sites, lower ^{137}Cs inventories as erosion sites and similar inventories as stable sites. Most soil samples (n = 35, 67%) had lower values than the ^{137}Cs reference inventory and were identified as eroded points. Eleven samples (21%) had values higher than the reference inventory and were identified as depositional sites. Only 6 samples showed values that fall within the stability range (see Table 3).

Comparing deposition and erosion sites, ^{137}Cs activity and inventory and SOM values showed significant differences, with lower values in the eroded sites. Significant differences were also observed between erosion and stable, and deposition sites related to ^{137}Cs activity and inventory. Excluding points below detection limit (see Fig. 2 Supplementary material) also significant differences were observed between deposition and stable points related to ^{137}Cs inventory. Otherwise, clay contents were similar and no significant differences were observed (Fig. 7, Table 3). On the other hand, comparing erosion and stable sites, significant differences were observed for silt and sand contents.

Fig. 6 also shows the distribution in the factorial plane of the deposition, erosion and stable sites. A strong discrimination between erosion and deposition and stable sites was observed. Erosion sites were on the negative side of PC1, clearly separated from deposition sites, and with low values of SOM and ^{137}Cs activity and inventory. Deposition and stable sites were distributed closely together along the positive side of PC1.

The spatial distribution of ^{137}Cs inventory showed high spatial variability in the Araguás catchment (Fig. 8). Areas of ^{137}Cs gain generally coincide with areas of high SOM values pointing to a recovery of soil layers particularly in the afforested part of the catchment (Fig. 8).

The sparsely vegetated areas recorded the highest soil erosion rates (121.9 Mg ha^{-1} yr^{-1}) while shrublands recorded the highest deposition rates (62.7 Mg ha^{-1} yr^{-1}). Mean soil erosion and deposition values were 68.6 Mg ha^{-1} yr^{-1} and 17.7 Mg ha^{-1} yr^{-1},

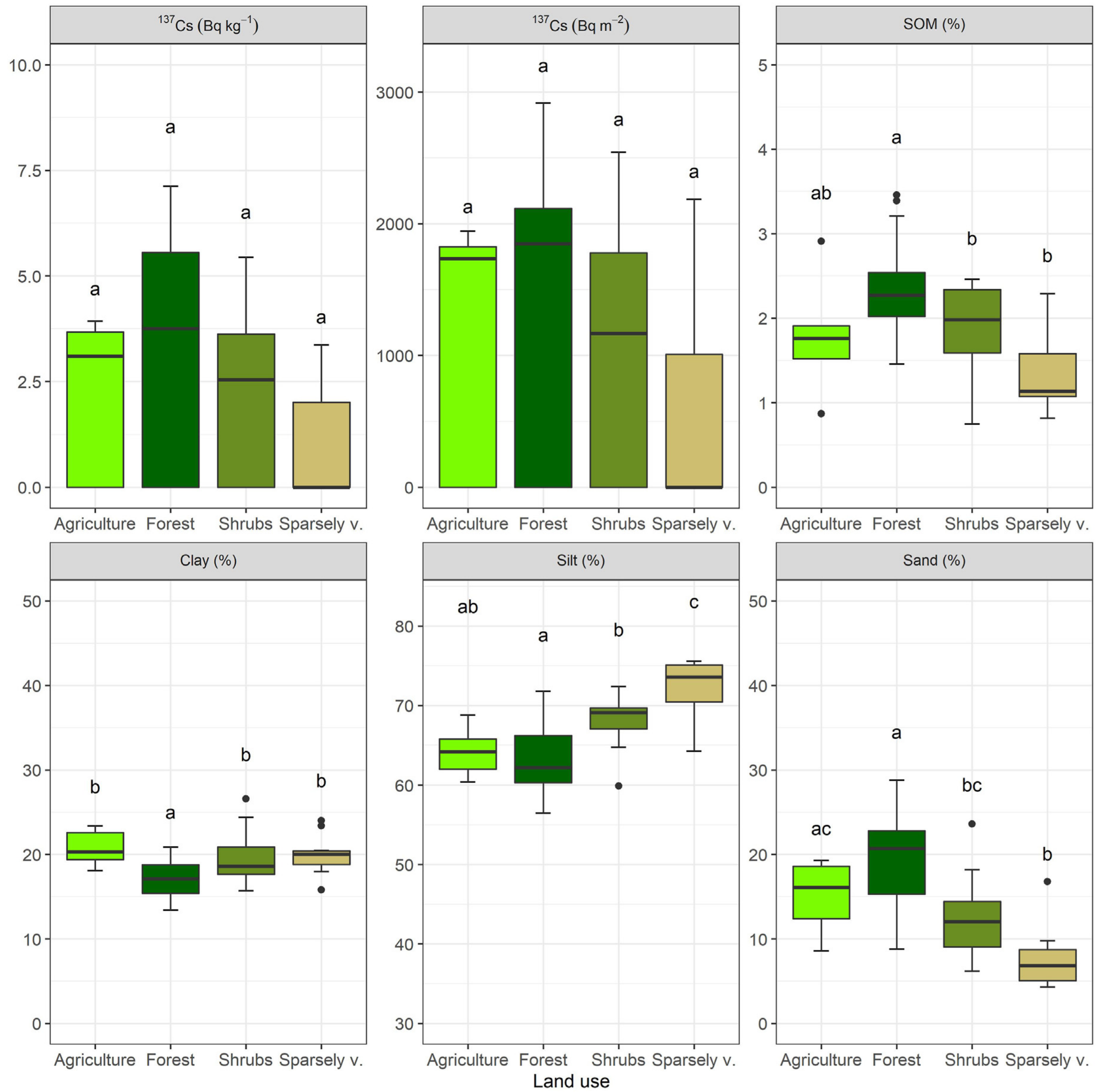


Fig. 3. Boxplot with land uses classification and soil properties: afforestation, natural revegetation, grassland, sparsely v. (sparsely vegetated areas, badlands). Note, significant differences were found between land uses in ^{137}Cs mass activity when excluding values below detection limits (see Fig. 1 Supplementary material) ($n = 52$). Note: SOM, soil organic matter.

Table 1
Basic statistics of the clay, silt, sand and soil organic matter (SOM) and ^{137}Cs activity and inventory in the Araguás catchment (all grid sampling points are considered, n=52). SD: Standard deviation, Max: Maximum value, Min: Minimum value, CV: Coefficient of variation.

		Clay (%)	Silt (%)	Sand (%)	SOM (%)	^{137}Cs activity (Bq kg^{-1})	^{137}Cs inventory (Bq m^{-2})
Soil samples	Median	18.8	67.4	13.5	2.0	2.5	1166.5
	Mean	18.9	67.1	14.0	1.9	2.2	1004.6
	SD	2.7	4.9	6.4	0.7	2.3	1032.6
	Max	26.6	75.6	28.8	3.5	7.1	2915.5
	Min	13.4	56.5	4.3	0.7	0.0	0.0
	CV	0.1	0.1	0.5	0.3	1.1	1.0

respectively. Most of the sparsely vegetated and pasture sites experienced soil erosion with a mean value of 68 Mg ha^{-1} yr^{-1} (ranging between −121.9 and 4.4 Mg ha^{-1} yr^{-1}) and 44 Mg ha^{-1} yr^{-1} (ranging between −110.0 and 8.4 Mg ha^{-1} yr^{-1}) respectively. Soil deposition was recorded in 45% of shrublands and afforested sites, with a mean value of 33 Mg ha^{-1} yr^{-1} in shrublands and 3.6 Mg ha^{-1} yr^{-1} in afforested sites. Soil erosion was recorded in 75% and 47% of the sampling points of shrublands and afforested sites with mean values of 64.2 Mg ha^{-1} yr^{-1} and 58.5 Mg ha^{-1} yr^{-1} respectively (Fig. 8). However, no significant differences in soil redistribution rates were found between the different LULC.

Table 2
Basic statistics of the clay, silt, sand and soil organic matter (SOM) and ^{137}Cs activity and inventory of the sampling points under the different land uses and land covers in the Araguás catchment (n = 52). SD: Standard deviation, Max: Maximum value, Min: Minimum value, CV: Coefficient of variation.

		Clay (%)	Silt (%)	Sand (%)	SOM (%)	^{137}Cs activity (Bq kg^{-1})	^{137}Cs inventory (Bq m^{-2})
Afforestation n = 17	Median	17.5	64.0	20.6	2.3	3.8	1847.0
	Mean	17.1	64.0	18.9	2.4	3.2	1333.6
	SD	2.2	4.9	6.1	0.6	2.7	1088.4
	Max	20.9	72.4	28.8	3.5	7.1	2915.5
	Min	13.4	56.5	8.8	1.5	0.0	0.0
	CV	0.1	0.1	0.3	0.2	0.8	0.8
Shrublands n = 20	Median	18.6	68.4	12.9	2.0	1.2	504.2
	Mean	19.5	67.8	12.7	1.9	1.9	939.9
	SD	2.8	3.0	4.8	0.5	2.0	1033.3
	Max	26.6	71.9	23.6	2.5	5.4	2544.0
	Min	15.7	59.9	6.2	0.7	0.0	0.0
	CV	0.1	0.0	0.4	0.3	1.1	1.1
Grasslands n = 5	Median	20.3	64.2	16.1	1.8	3.1	1733.3
	Mean	20.8	64.2	15.0	1.8	2.1	1100.0
	SD	2.2	3.3	4.5	0.7	2.0	1006.9
	Max	23.4	68.8	19.3	2.9	3.9	1942.4
	Min	18.1	60.4	8.6	0.9	0.0	0.0
	CV	0.1	0.1	0.3	0.4	0.9	0.9
Sparsely vegetated areas n = 10	Median	20.0	73.6	6.8	1.1	0.0	0.0
	Mean	20.0	72.4	7.6	1.3	0.9	526.7
	SD	2.4	3.6	3.7	0.5	1.5	871.1
	Max	24.0	75.6	16.8	2.3	3.4	2185.5
	Min	15.8	64.3	4.3	0.8	0.0	0.0
	CV	0.1	0.1	0.5	0.4	1.6	1.7

4. Discussion

4.1. Soil properties in the reference sites

The legacy of the historic land use and land cover changes, and their distribution across the Araguás catchment is a key factor in the spatial patterns of soil redistribution processes.

The depth distribution of ^{137}Cs in the reference profiles followed the typical pattern (exponential decline) of undisturbed areas in mountain regions (Navas et al., 2005; Quijano et al., 2016). Most of the ^{137}Cs was found in the upper part of the soil (above 15 cm), and the reference inventory falls within the range (1475–2288 Bq m^{-2}) estimated by Legarda et al. (2011) and Caro et al. (2013) for the Iberian Peninsula, although is lower than the local reference inventory of around 4500 Bq m^{-2} obtained in the neighbouring Aisa Valley by Navas et al. (2005, 2017) due to its higher annual rainfall and the radionuclide decay. An exponential decrease was also observed with SOM contents, confirming that the soil remains undisturbed after ^{137}Cs fallout. It is interesting to note the retention of ^{137}Cs in the first topsoil layers at the reference sites, that is attributed to firm bounds of ^{137}Cs to organic matter, as indicated by its significant correlation with ^{137}Cs mass activity (Gaspar et al., 2013; Kim et al., 2006).

4.2. Soil properties in the Araguás catchment (grid samples)

Soil changes can take a long-time to build up, and consequently the effects of afforestation after cropland abandonment can be sometimes limited (Iroumé & Palacios, 2013; Maestre & Cortina, 2004). In the Araguás catchment, the interpolation of soil properties showed a large variation, and significant differences between LULC were observed under mean SOM and particle size contents and ^{137}Cs. Higher values of SOM contents and ^{137}Cs were recorded in afforested sites compared with shrublands and sparsely vegetated areas, while no differences were observed with pasturelands. These results suggest that LULCC are one of the principal factors affecting the variation of soil properties and redistribution, as has been found in previous studies (Navas et al., 2008; Lizaga et al., 2019, among others).

The results of this study show that soils in the Araguás catchment after LULCC are prone to degradation, as indicated by a generalized loss of ^{137}Cs compared to the reference inventory: 67% of the sampling sites were affected by ^{137}Cs loss. As the presence of ^{137}Cs is associated with the presence of clay (Forkapic et al., 2017), the homogeneous depth-distribution of clay in upper layers and its enrichment at the deeper layers along with the limited range of variations in the Araguás catchment (92% of the samples show a clay content between 15 and 25%), may explain the preferential fixation of ^{137}Cs with SOM. The highest activity of ^{137}Cs in the afforested area is related with the strong positive relationships between ^{137}Cs and SOM (Fig. 5), confirming that ^{137}Cs remain strongly fixed to the organic matter (i.e., Gaspar et al., 2021). In that sense, Rigol et al. (2002) and Lizaga et al. (2018) indicated that SOM is determinant in the adsorption of ^{137}Cs, being a highly efficient mechanism for fixing ^{137}Cs in the soil. Most of the sites with high SOM contents were recorded in the afforested areas, as a consequence of constant organic matter accumulation in the organic and mineral horizons due to litter deposition and stabilization processes.

4.3. Implications on soil redistribution

The ^{137}Cs values in the Araguás catchment suggest that erosion and deposition processes were active in the last 50–60 years showing soil losses and gains. The predominance of clay and silt-loam textures with mean silt contents around 60% together, with low SOM contents (<2%) could explain the low resistance to particle detachment and erosion and transport processes (i.e. Loveland & Webb, 2003). Soil loss was associated with all LULC (mean value 69 Mg ha^{-1} yr^{-1}), with more critical values in badland areas (maximum value of 122 Mg ha^{-1} yr^{-1}). Furthermore, the lowest values of ^{137}Cs and SOM and the highest slope gradients were found under the sparsely vegetated sites in the badland areas. These results can be linked to the intense geomorphological dynamics in

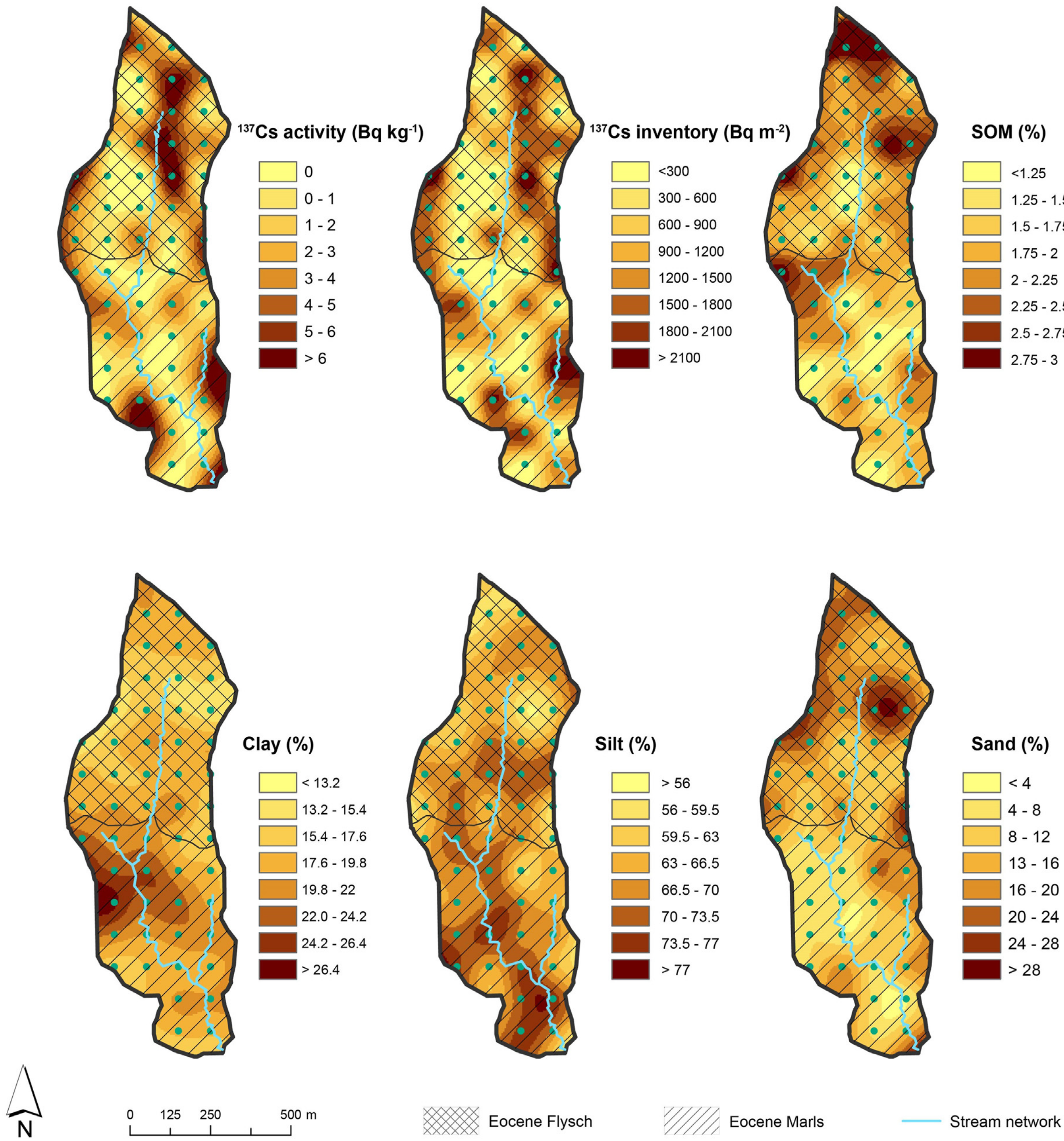


Fig. 4. Spatial distribution of ^{137}Cs activity and inventory, SOM, clay, silt and sand contents in the Araguás catchment produced by an ordinary kriging. The stream gauge is also shown. Note: SOM, soil organic matter. The green points indicate the sampling sites.

these areas, related to physico-chemical weathering processes, erosion processes and the high hydrological and sedimentological dynamics recorded in the catchment (Nadal-Romero & Regüés, 2010). Scientific literature shows that erosion rates in badlands are greater than in other landforms and LULC (Nadal-Romero & García-Ruiz, 2018): in humid Mediterranean badlands high sediment yield, exceeding 500 Mg ha^{-1} was recorded (Brochot, 1993), and most of the studies concluded that annual sediment yield resulted mainly from a small number of maximum events (Mathys et al., 2005; Regüés et al., 2000). In the dryer conditions of the Moroccan Rif the highest rates of soil loss were also recorded with ^{137}Cs in badlands in comparison to other land uses (Sadiki et al., 2007). These results, confirm the values obtained through the continuous monitoring of the Araguás catchment with an average sediment yield of 153 Mg ha^{-1} yr^{-1} over the entire study area, or 575 Mg ha^{-1} yr^{-1} from badland areas. However, as it has been highlighted by different authors, each measurement method is appropriate to address a particular scientific question. In that sense, García-Ruiz et al. (2015) highlighted that soil erosion results are not independent of the method used, because each method tends to be related to a spatial scale or a range of spatial scales and focus on different soil erosion processes.

The long history of human activity through agricultural practices and active restoration practices (afforestation) have determined the intense degradation values recorded in the Araguás catchment. Soil erosion during the cultivation and after land abandonment was severe in steep slopes in mountain areas (Navas et al., 2017). In these areas, a period of intense erosion is usually observed after cropland abandonment (García-Ruiz & Lana-Renault, 2011): (i) lands were abandoned after the harvest, with

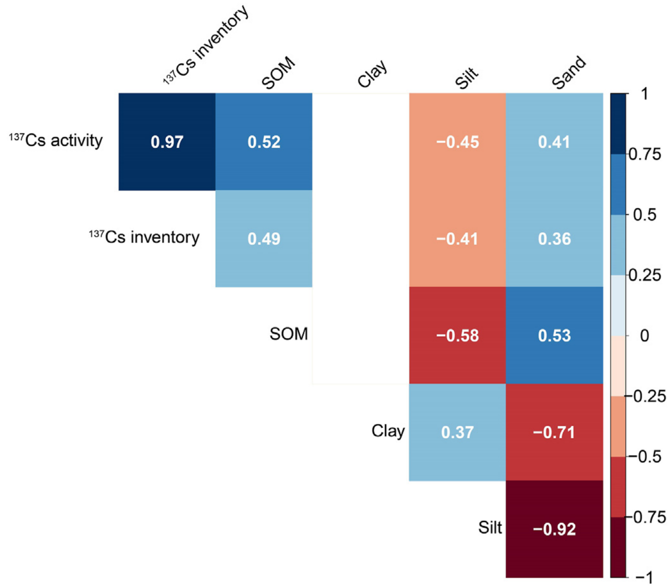
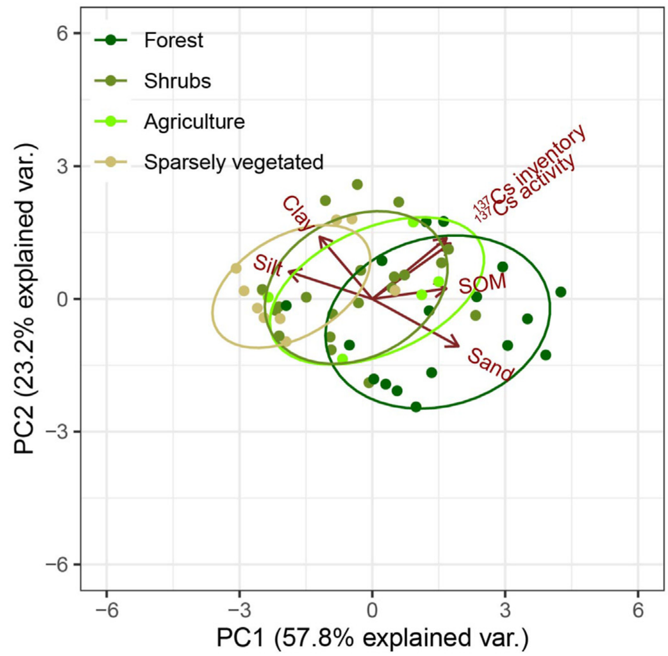


Fig. 5. Correlation matrix of the main soil properties in the Aragúas catchment. Note: SOM, soil organic matter (n = 52). Only significant values at 95% confidence level are showed in the figure.



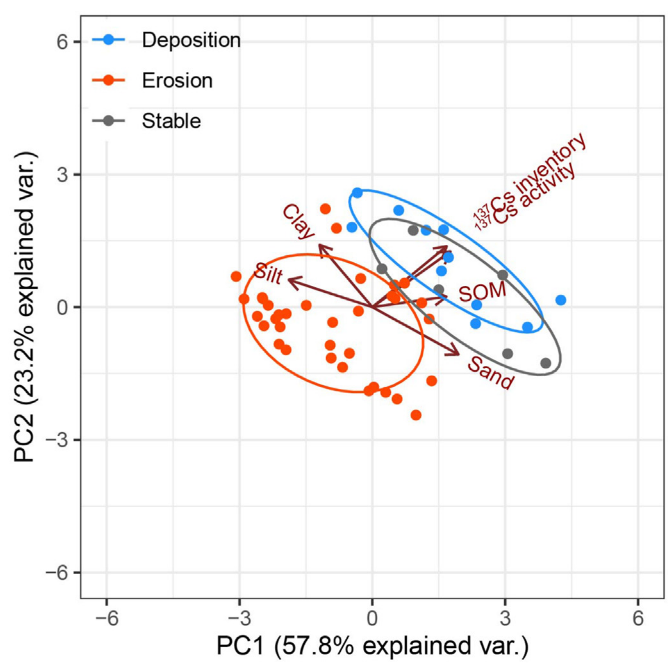


Fig. 6. Dispersion diagram plots and principal component loadings of the two first components from a PCA for the complete set of soil samples. LULC and deposition, erosion and stable sites were also represented in the plots. Note: SOM, soil organic matter.

high percentage of bare soil, coinciding with intense rainfall events enhancing crust development, high runoff values and soil erosion processes (García-Ruiz et al., 1995; Navas et al., 2008); (ii) terraces and stone walls were abandoned and no longer maintained (Moreno de las Heras et al., 2019); (iii) most of the practices used in afforestation increase soil erosion (Nunes et al., 2011); (iv) poor (low soil organic matter level after decades on human activities) and bare soils in the abandoned areas, and the slow growth of the coniferous plantation limited the re-growth of grassland and shrubs that could protect the soils during the first years (de Wit & Brouwer, 1997).

Afforestation in the Araguás catchment was carried out in the highest and steepest areas, that in addition were the less accessible and consequently were the first abandoned. The early abandonment of the area and the afforestation at the end of the 1960's likely contributed to intense soil redistribution processes. Extensive afforestation was carried out after cropland abandonment in an attempt to control land degradation and soil erosion processes (Nunes et al., 2011). However, the used planting techniques have a direct effect on soil loss and properties and can fully truncate the soil profile. Such effects occur during the first years of tree development because soil surface remains unprotected, accelerating erosion processes (Chaparro & Esteve, 1995; de Wit & Brouwer, 1997; Romero-Díaz et al., 2010). Thus, although the lowest soil redistribution rates were recorded in the afforested sites, no significant differences were recorded between shrubs and afforested areas, contrarily to other results recorded in Mediterranean mountain areas (Navas et al., 2005, 2011). We hypothesized that, before restoration, high soil erosion processes occurred in the afforested area due to decades of cultivation. These erosion processes were intensified during restoration due to the used afforestation practices. In that sense, literature confirms this hypothesis: de Wit and Brouwer (1997) observed an increase in soil erosion processes at least during the 14 years after planting, Chaparro and Esteve (1995) observed an increase in the geomorphic activity even 20 years after planting using terracing and heavy machinery and Nunes et al. (2011) showed that erosion in afforested plots was very high in comparison with other LULC. However, contrary to our results, other studies carried out in Mediterranean mountain areas with a different legacy of the historic land use changes have identified significant differences between LULC: Navas et al. (2005, 2008) found differences between shrubland and forest sites, and Lizaga et al. (2018) between agricultural and afforested and shrubland areas.

In the Araguás catchment, afforestation was installed in low fertile soils, and during the first years after restoration soil erosion was high. However, certain changes in soil properties, such as the increase in soil organic matter content and soil aggregation (Nadal-Romero et al., 2016b) suggest a decrease in soil erosion processes in the afforested area in the last decades. Important changes have been observed related to organic matter quality and aggregation:

Table 3
Mean values of soil properties at erosion, deposition and stable points under the different land uses and land cover in the Araguás catchment (n = 52). Note: SOM, soil organic matter.

	n	Clay (%)	Silt (%)	Sand (%)	SOM (%)	^{137}Cs activity (Bq kg^{-1})	^{137}Cs inventory (Bq m^{-2})
Erosion n = 35	**T**	**19.2**	**68.5**	**12.3**	**1.7**	**0.9**	**418.9**
Afforestation	8	17.7	65.3	17.0	2.2	0.8	346.1
Shrubland	15	19.4	68.4	12.2	1.7	1.0	471.9
Pastureland	3	20.0	65.6	14.4	1.4	1.0	577.8
Badland	9	19.9	72.4	7.7	1.3	0.7	342.4
Deposition n = 11	**T**	**18.3**	**65.6**	**16.1**	**2.3**	**5.2**	**2394.3**
Afforestation	5	16.4	63.8	19.8	2.4	6.3	2486.3
Shrubland	5	19.7	66.0	14.3	2.2	4.5	2344.0
Pastureland	–	-	-	-	-	-	-
Badland	1	30.5	72.2	7.3	1.9	3.4	2185.5
Stable n = 6	**T**	**18.4**	**62.1**	**19.6**	**2.7**	**4.1**	**1872.9**
Afforestation	4	16.6	62.9	21.5	2.9	4.2	1867.7
Shrubland	–	–	–	–	–	–	–
Pastureland	2	21.9	62.3	15.8	2.4	3.8	1883.3
Badland	–	-	-	-	-	-	-

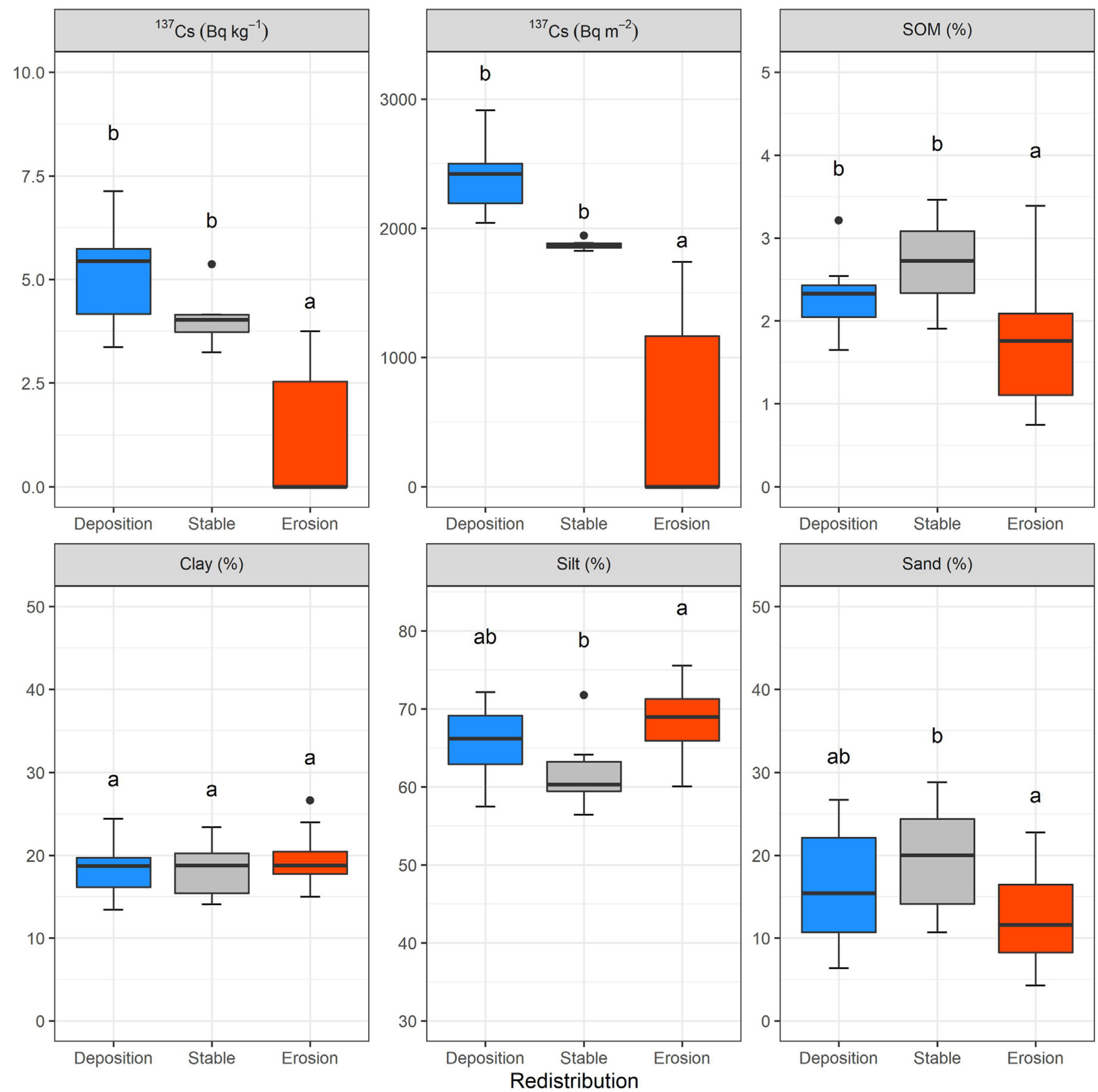


Fig. 7. Box plot of erosion, deposition, and stable sites with soil properties values. Note: SOM, soil organic matter. Note, significant differences were found in ^{137}Cs inventories when excluding values below detection limits (see Fig. 2 Supplementary material).

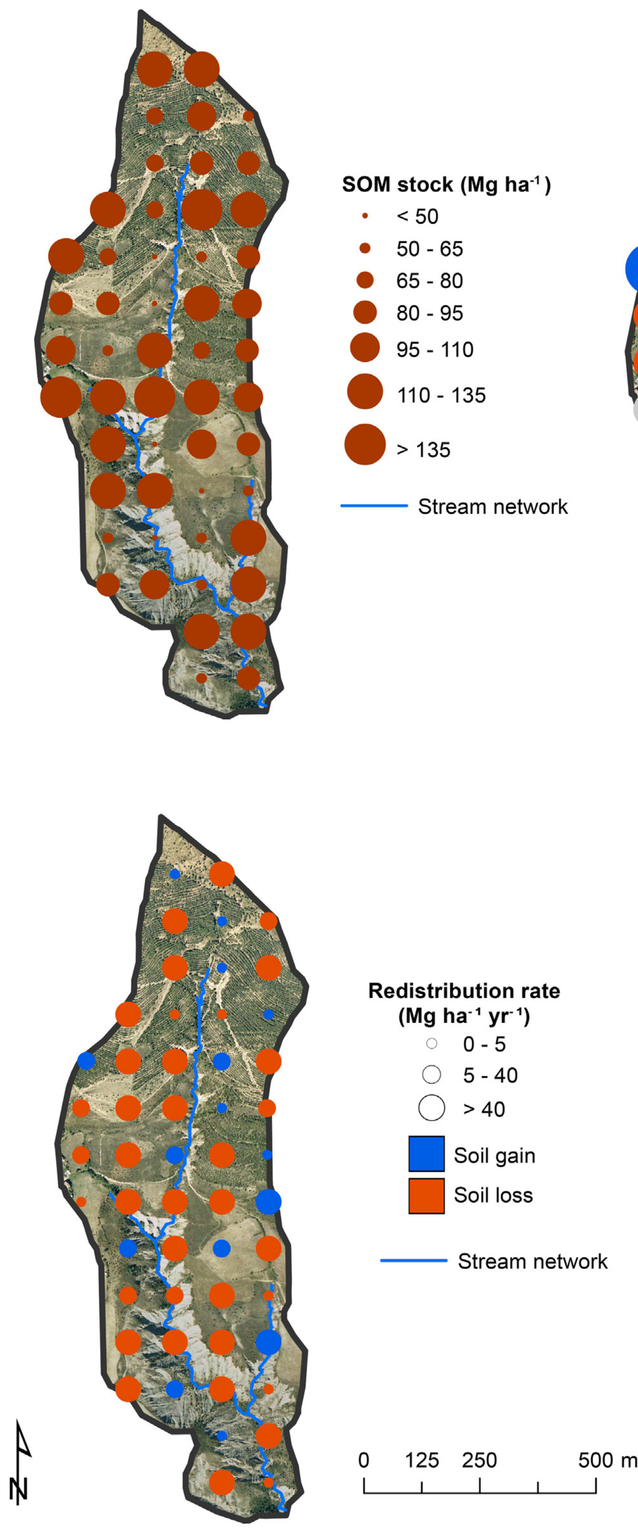


Fig. 8. Spatial distribution of ^{137}Cs and SOM inventories and redistribution rates. Note: SOM, soil organic matter.

higher aggregation and high carbon accumulation in macroaggregates (>5 mm) (Nadal-Romero et al., 2016b) and higher lignin content (Campo et al., 2019). Similar results were described in LaManna et al. (2021).

4.4. Management consideration

Radiotracers approaches offer a considerable potential to study erosion processes and quantify soil redistribution rates. The radioactive fallout of ^{137}Cs has been successfully applied in Mediterranean mountain environments for studying not only soil erosion but also the mobilisation of nutrients associated to soil particles. As it has been showed in this research, this technique provides medium-term spatially distributed soil redistribution rates, representing annual values for the last 60 years, that has been an intense period of LULCC in mountain areas after cropland abandonment. Future studies using soil erosion modelling (i.e. WATEM/SEDEM) and ^{137}Cs information for the validation of distributed soil erosion (will allow simulating soil redistribution under past, current and hypothetical future LULC scenarios (Lizaga et al., 2022), based on revegetation conditions in Mediterranean mid-mountain areas. These expected results would support the development of soil conservation strategies which may help to mitigate soil degradation processes after cropland abandonment in a context of Global Change. This is an important issue, because complex computerized models indicate that land abandonment will continue in the next decades (Keenleyside & Tucker, 2010, p. 93), therefore, post-land management practices, such as afforestation programs, should be reviewed in the design of future restoration plans and soil conservation strategies in Mediterranean mountain areas.

5. Conclusions

Land use and land cover changes (LULCC), due to passive (through natural revegetation) and active restoration (through afforestation), in Mediterranean mid-mountain areas, affect soil properties and redistribution. Significant differences were found between land uses and land covers (LULC) in soil properties and ^{137}Cs inventories. However, contrarily to our hypothesis, no differences were observed between the different LULC in soil redistribution rates. These results are due to a long history of human intervention through cultivation in steep slopes and afforestation practices. suggesting that the legacy of the historic vegetation changes and its spatial distribution across the Araguás catchment is determinant in soil redistribution processes. On the other hand, the high values of SOM contents in afforested areas suggest that afforestation can reduce soil degradation after cropland abandonment at long-term scale. This finding was reinforced by the higher erosion rates recorded under sparsely vegetated sites in the badland area, while the lower rates were found in the afforested area.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.iswcr.2022.10.001.

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