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How do land use and land cover changes after farmland abandonment affect soil properties and soil nutrients in Mediterranean mountain agroecosystems?

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ABSTRACT

Mediterranean mountains are sensitive agroecosystems that have suffered intense land use and land cover changes (LULCC) during the last century. From the middle of the twentieth century, most of the cultivated lands in Mediterranean mountains were abandoned, allowing the recovery of vegetation (through natural revegetation and afforestation programmes). To examine the effects of farmland abandonment, secondary succession (natural revegetation) and afforestation, an intensive soil sampling was carried out in the Araguás catchment (Central Spanish Pyrenees) including sparsely vegetated areas (badlands), grasslands, shrublands and afforested sites. LULCC were mapped, and soil physico-chemical properties were analysed in reference sites (unaltered areas during the last centuries) and in the different land uses. Likewise, the soil organic carbon (SOC) content in the bulk soils and in the fractions separated by density fractionation have been studied. This study evidenced that farmland abandonment led to a mosaic landscape with different land use and land covers. Results show that LULCC significantly affect soil physico-chemical properties (soil texture, stoniness, pH, SOC, total carbon, CorgN ratio, bulk density and field capacity). Significant differences were observed between secondary and afforested sites following farmland abandonment. Afforestation triggered higher SOC than shrubland sites (natural revegetation) (1.4 and 1.1% respectively), suggesting a slower process of organic matter accumulation after farmland abandonment in the natural revegetation compared to afforestation. The significant role of grassland sites for enhancing the accumulation of SOC has been also confirmed. The results showed also significant differences in the relative contribution of each organic fraction to the bulk SOC: the amount of labile fraction (free and occluded labile fractions) is significantly higher in afforested and shrubland sites (58.1 and 51.2% respectively) than in grassland sites (36.8%). Understanding the effects of LULCC on soil properties and SOC dynamics is essential when planning post-land management practices after farmland abandonment.

1. Introduction

Land use and land cover changes (LULCC) often occur in agroecosystems (Varela et al., 2020; Padial-Iglesias et al., 2022). In the Mediterranean region, farmland abandonment and revegetation processes are one of the most important ones, with wide-reaching socioeconomic and environmental consequences. The increase in biodiversity (San Román-Sanz et al., 2013; García-Llamas et al., 2019), the reduction of soil erosion (García-Ruiz and Lana-Renault, 2011), and greater soil organic carbon stocks (Bell et al., 2021; Lasanta et al., 2021) are among the main positive impacts of farmland abandonment. However, the negative impacts include the increase of fire risk (Oliveira et al., 2014), landscape homogenization (Jongman, 2002), and the decrease of water resources (López-Moreno et al., 2011) among others.

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Farmland abandonment is a worldwide process that is also affecting traditional livelihoods altering environment and economy (Rescia et al., 2008; Gretter et al., 2018; Bernués et al., 2019). In southern Europe, 24.5% of the lands under annual and permanent crops were abandoned between 1961 and 2011 (Gabarrón-Galeote et al., 2015): for instance, in the Central Spanish Pyrenees, since the end of the 19th century, Lasanta-Martínez (1988) indicated that 71% of farmland has been abandoned, and Lasanta et al. (2001) noted that in Cameros Viejo (north-western Iberian Range, Spain) 99% of agricultural land was abandoned. The extent of abandonment has been also observed in the mountains in Poland (Kozak et al., 2004), Slovakia (Kuemmerle et al., 2008), and the French Prealps (Taillefumier and Piégay, 2003) where around 20% of farmland has been abandoned, and around 30% in the Carpathians (Hostert, 2010). In Central and Eastern Europe, Van Dijk et al. (2004) stated that between 10% and 20% of agricultural land has been abandoned. It is an ongoing trend, and about 11% of the agricultural European land is under high risk of abandonment in the coming 10 years (Perpiña Castillo et al., 2018), estimating that 5.6 Mha of land will be subject to abandonment by 2030 in Europe (Perpiña Castillo et al., 2021). More recently, the process of farmland abandonment is also occurring in other parts of the world (Yin et al., 2020), such as Brazil (Castro et al., 2020; Reichert et al., 2022), Mexico (Contreras-Cisneros et al., 2022), and China (Zhang et al., 2023). For all these reasons farmland abandonment should be perceived as a policy challenge (van der Zanden et al., 2017).

The drivers of farmland abandonment are very diverse, due to the interaction of global and local causes (Allison and Hobbs, 2006; Mottet et al., 2006; Verburg et al., 2007). Among the global causes, or external to a place, the scientific literature preferably includes: market dynamics and globalisation, public policies, labour demand by industry or the service sector involving the migration of the population from rural to urban areas, and technological and institutional changes (Lambin et al., 2001; Strijker, 2005; Sluiter and de Jong, 2007); while internal or local causes include ecological factors (climate, soil, topography, erosion) and the characteristics of livestock farms (location, size and ownership), as they condition the production and access to markets (Veysset et al., 2005; Rey Benayas et al., 2007; Van Vliet et al., 2015). Lasanta et al. (2017) concluded that global causes act as triggers of the abandonment process, while local causes condition the total abandoned surface and the areas that are abandoned, as they determine the productivity and, ultimately, the profitability and competitiveness of the product offered.

Land abandonment generates important changes in soil properties, due to soil tillage suspension and vegetation colonization (natural or managed) and post-land management practices (i.e. pasture establishment) that changes physico-chemical soil properties and soil quality (i.e. Zhang et al., 2012; van Hall et al., 2017; Gaspar et al., 2019; Lizaga et al., 2019). Natural revegetation processes and afforestation after farmland abandonment are different strategies to restore soil ecosystem services, such as nutrients, soil conservation and carbon sequestration (Bell et al., 2020), as well as a progressive improvement in soil characteristics (Lasanta et al., 2020). The main soil property studied after farmland abandonment is soil organic carbon (SOC) content and its variation over time (i.e. Bell et al., 2021; Sciubba et al., 2021). Carbon sequestration is one of the crucial factors which affects global climate change mitigation, as it has been highlighted in international reports, such as the Kyoto Protocol (article 3.3) or the Paris Agreement, including it as an important element for managing and reducing greenhouse emissions. Thus, the impact of farmland abandonment and revegetation processes, as well as, the role played as sources and sinks of SOC, have received increasing attention during the last decade (Navas et al., 2012; Lizaga et al., 2019; Bell et al., 2021; Nadal-Romero et al., 2021; Contreras-Cisneros et al., 2022). However, the dynamics of SOC are governed by its distribution into various pools or fractions, with contrasting behaviours and rates of turnover and that are differently affected by farmland abandonment and post-land management practices (Sanaullah et al., 2019). The method proposed by Golchin et al. (1994) for density fractionation identified labile fractions (Free Light Fraction (FLF) composed mainly by undecomposed labile organic matter, and Occluded Light Fraction (OLF) composed by organic matter stabilized by aggregation) having a low mean residence time of days, months, or years, and the Heavy Fraction (HF) that is strongly associated with soil minerals having a higher mean residence time of decades to centuries (Lavallee et al., 2020).

This study aims to assess the effects of farmland abandonment and post-land abandonment management (through natural revegetation and afforestation) on soil properties and soil nutrients (soil organic carbon and nitrogen contents) in a Mediterranean mountain area. The specific objectives are to (i) quantify land use changes during the last 60 years in the Araguás catchment (Central Spanish Pyrenees) as a representative area of LULCC, (ii) assess at catchment scale the spatial patterns of soil properties and soil nutrients, soil organic and inorganic carbon, total nitrogen related to LULCC, and (iii) quantity changes in isolate organic carbon density fractions in afforested pine forests, natural shrublands, grasslands and sparsely vegetated areas. This leads to the following research hypotheses: (i) LULCC after farmland abandonment and post-land abandonment practices have a significant impact on soil nutrients and soil properties, and (ii) afforestation can accelerate the recovery of specific soil properties and nutrients after farmland abandonment compared to natural revegetated areas, although also other management options should be considered.

2. Materials and methods

2.1. Study area

The Araguás catchment is a small north–south catchment (0.45 km^2) in the Central Spanish Pyrenees. The catchment has an altitude between 780 and 1100 m. a.s.l., and is largely occupied in the lower part by badlands (Fig. 1), while abandoned fields in different stages of natural succession or afforested are spread alongside the headwater. Mean annual precipitation of 800 mm and annual temperature of 10 °C characterizes the sub-Mediterranean climate of the catchment influenced by oceanic and continental regimes. Bedded thin layer of sandstones and marls form the main lithology of the catchment (Eocene marls in the lower part of the catchment and Eocene flysch in the headwater). The generalized steep slopes and the intense cultivation history of the catchment resulted in stony shallow soils formed mainly by Calcaric Leptic Regosols following the WRB taxonomy (IUSS Working Group WRB, 2015) although Leptosols are developed in the upper part of the catchment.

Before abandonment, the Araguás catchment was heavily cultivated with cereal crops in terraced fields that smoothed its hillslopes. By the end of the 1960ies, the upper part of the catchment was afforested with pine trees (*Pinus nigra* and *Pinus sylvestris*) while most of the abandoned fields underwent a natural revegetation process and were colonized by shrub species (*Juniperus communis*, *Genista scorpius*, *Rosa gr. canina* and *Buxus sempervirens*). These land use changes resulted in a current complex mosaic landscape alternating pine afforestation (Fig. 1A), shrublands (Fig. 1B), grasslands (Fig. 1C), and sparsely vegetated areas where the presence of badlands is apparent (Fig. 1D).

2.2. Experimental sampling design

In 2019 a total of 52 bulk core soil samples were collected. A steel core tube was used to collect 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. The sampling points were distributed proportionally across the catchment surface using a 100 × 100 m grid with a sampling density of 1.2 ha/sample (see Fig. 1A).

In order to establish the local reference inventory of the soil properties for the Araguás catchment, 9 sectioned core samples were collected in reference sites (see Khorchani et al., 2022). Reference sites

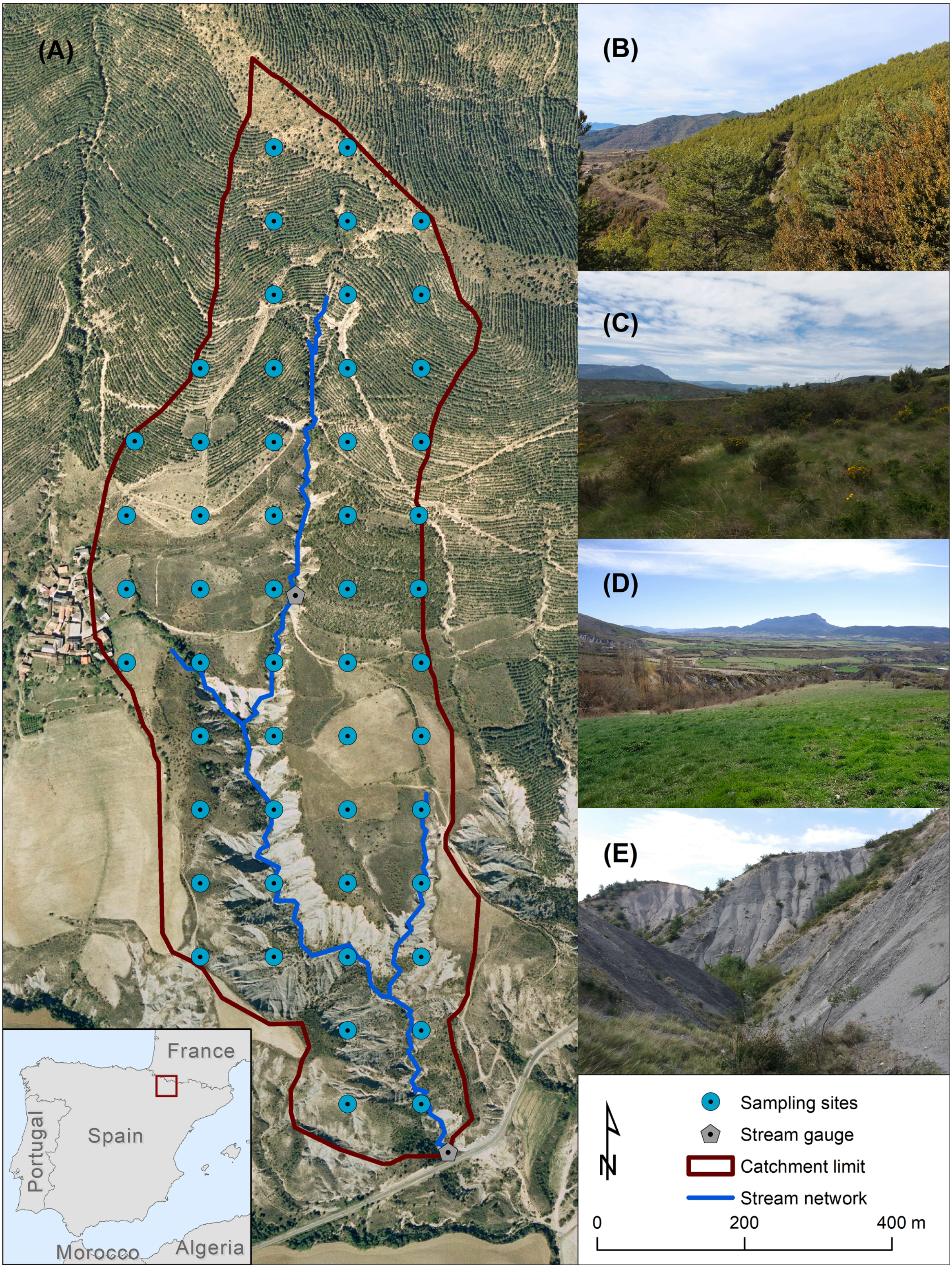

Fig. 1. Location of the Araguás catchment (Central Spanish Pyrenees) and overview of the present land use and land cover: (B) Afforested sites; (C) Shrubland sites; (D) Grassland sites; (E) Sparsely vegetated badlands sites.

correspond with flat undisturbed vegetated areas under stable conditions, where neither deposition or erosion processes were expected to have occurred during the last decades. In addition, top soil samples (first 5 cm) were sampled in each point to carry out density fractionation analysis from the top soil layers.

2.3. Laboratory analysis

The two soil cores from each sampling site were air-dried in the laboratory then mixed, homogenized and sieved over a 2 mm. The following physico-chemical soil properties were determined in the laboratory (at the Pyrenean Institute of Ecology (IPE-CSIC), the Experimental Station of Aula Dei (EEAD-CSIC), and the Institute for Biodiversity and Ecosystem Dynamics (UvA-IBED)): (i) electrical conductivity (EC) and pH were measured in a deionized water suspension (1:2.5) using a pH meter and a conductivity meter; (ii) the > 2 mm fraction was weighed in order to account for the stone content (% stoniness), (iii) particle size analysis was carried out with a Beckman Coulter LS 13 320 laser diffraction particle size analyser (Beckman Cboulter Inc., 2011) after oxidizing the organic matter by pre-treating the soil with H_2O_2 (10%) in a boiling water bath at 80 °C and adding 2 ml of solution of a dispersing agent (40% sodium hexametaphosphate to avoid grain flocculation); (iv) total carbon (TC), soil organic carbon (SOC) and total nitrogen (TN) were measured by dry combustion in an elemental analyser (LECO CNS 928, Leco Corporation); (v) CorgN ratio was calculated using SOC and TN; (vi) bulk density (BD) was estimated from undisturbed cores that were oven-dried at 105 °C for 24 h, (vii) $CaCO_3$ (%) was determined through the Bernard Calcimeter; and (viii) soil hydraulic properties (saturated soil moisture (Sat), field capacity (FC) and permanent wilting point (PWP)) were estimated using pedrotransfer functions (from texture data and organic matter values; Rawls et al. (1992)).

Density fractionation methodology was applied on non-sieved top soil samples (5 cm) following the methods of Golchin et al. (1994) and Cerli et al. (2012). Due to the time needed to fractionate soil samples, a smaller set was selected and 32 samples were analysed. Ten grams of soil were weighted in a centrifuge tube and 50 ml of sodium polytungstate (NaPT) of a density of 1.6 g cm^{-3} was added. The suspension stood for 1 h and after this time it was centrifuged at 6800 g for 20 min at room temperature. The floating material (free light fraction, FLF) was separated and collected on a 0.7 µm pore glass-fibre filters (Whatman GF/F filter), by using a rubber spatula, and washed with deionized water till the conductivity of the washing water was 200 µS cm^{-1}. The remaining soil was re-suspended into 50 ml of NaPT and then dispersed by ultrasound at 150 J mL^{-1} (Sonopuls HD 3200 with VS70 probe), calibrated according to Schmidt et al. (1999) in an ice-bath to keep the temperature (40 °C). After the dispersion process, the samples were again centrifuged; the floating material (constituted the occluded light fraction, OLF) was then separated, filtered and washed with deionized water (as above described for the FLF). The remaining sample was washed by repeated addition of deionized water, shaked and centrifuged (10,000 g to ensure complete sedimentation of the smallest clay-size particles), until the conductivity of the wash water was by 500 µS cm^{-1}. The soil material (heavy fraction, HF) was then transferred into dark containers. All fractions were freeze-dried, homogenized (the HF was milled) and used for the determination of SOC, TN, CorgN ratio. In the HF the $CaCO_3$ content was also determined through the Bernard Calcimeter.

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. The homogeneity of variance using Levene's test was also tested. Pearson's correlation coefficients were used to assess the relationships between the different physico-chemical soil properties and soil nutrients. 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. In all cases, we considered differences to be statistically significant at $p < 0.05$. All statistical analyses were carried out using R 3.4.3.

Finally, an ordinary kriging with constant trend was selected to display the spatial distribution of soil properties at the catchment scale. All the output maps and interpolations were performed using ESRI ArcGis software.

3. Results

3.1. Land use and land cover changes

Fig. 2 and Table 1 show the LULCC in the Araguás catchment from 1957 related to the afforestation of the upper part of the catchment and the colonization of most of the abandoned fields by a natural revegetation cover. By the end of the 1950ies shrubs occupied 62.0% of the catchment while the remaining agricultural areas represented 21.2% of its surface. The process of land abandonment continued after 1957 and reduced the total agricultural area in the catchment to the half by 2018 (9.7% corresponding to grassland areas). On the other hand, active management plans of abandoned agricultural lands led to the afforestation of large areas in the Central Spanish Pyrenees. These management plans resulted in the afforestation of most of the upper part of the catchment by the end of the 1960ies. In 2018, the total afforested area represented 33% of the catchment contributing to an important decline in the shrub area that decreased to 41.7%, beside shrub colonization of the new abandoned fields.

3.2. Physico-chemical soil properties in the reference sites

Table 2 and Fig. 3 show the physico-chemical soil properties at the nine reference sites. In general, soils in the undisturbed areas were moderately developed. The coarse fraction was homogeneously distributed through the soil profile. Soils are stony with average amounts around 23.6%, reaching 58.7%. Silt fraction predominated with mean values around 41.2%. The mean values of clay and sand were 31.4 and 27.4%, respectively. Mean pH and EC values in the reference 5 cm intervals were 8.3 and 369 µS cm^{-1} respectively. The mean contents of SOC and TN were 1.6% and 0.2% respectively, ranging between 0.3 and 5.7% and 0.1 and 0.4%. Mean CorgN ratio was 9.0, ranging between 3.9 and 18.0. The mean saturation point, field capacity and permanent wilting point were 0.5, 1.3 and 0.2 respectively.

The reference profiles showed an exponential decrease of sand, SOC, TN, CorgN from the surface to the deepest layers (Fig. 3). The clay fraction showed a slightly increase with depth, and silt content was distributed relatively uniform with depth, and had no significant differences between the top and deep soil layers. In addition, a slight increase in pH and field capacity values was recorded.

3.3. Physico-chemical soil properties in the grid points of the Araguás catchment

In the Araguás catchment soils are alkaline and non-saline. Soils were stony with average stoniness around 22%, reaching a maximum value of 43%. All the samples had a silt-loam texture with a predominance of silt (mean value of 67%), ranging between 57% and 76% (Fig. 4). Sand content oscillated between 4% and 29% (mean value of 14%), and clay content ranged between 13% and 27% with a mean value of 19%. Mean pH and EC values were 8.4 and 212 µS cm^{-1} respectively, and high carbonate content was observed (39%). The mean contents of SOC and TN were low, ranging from 0.4% to 2.0% (mean value 1.1%) and 0.1% to 0.3% (mean value 0.1%) respectively. CorgN ratio oscillated between 4.5 and 12.4 with a mean value of 8.3 ± 2.1. Only in the afforested sites, the CorgN ratio was generally higher than 10, considering this value optimal for the best incorporation rate of the organic matter into the soil profile (Table 3).

Significant differences were found between LULC (Fig. 4). Related to soil texture, silt and clay contents were significantly lower in the afforested areas compared with shrublands and sparsely vegetated areas. The means of clay, silt, sand, SOC, CorgN ratio, bulk density and field capacity in the afforested sites significantly differed from those in the shrubland sites. pH values were higher in the sparsely vegetated areas and significant differences were also found for silt, sand and pH values between grasslands and sparsely vegetated areas. Only,

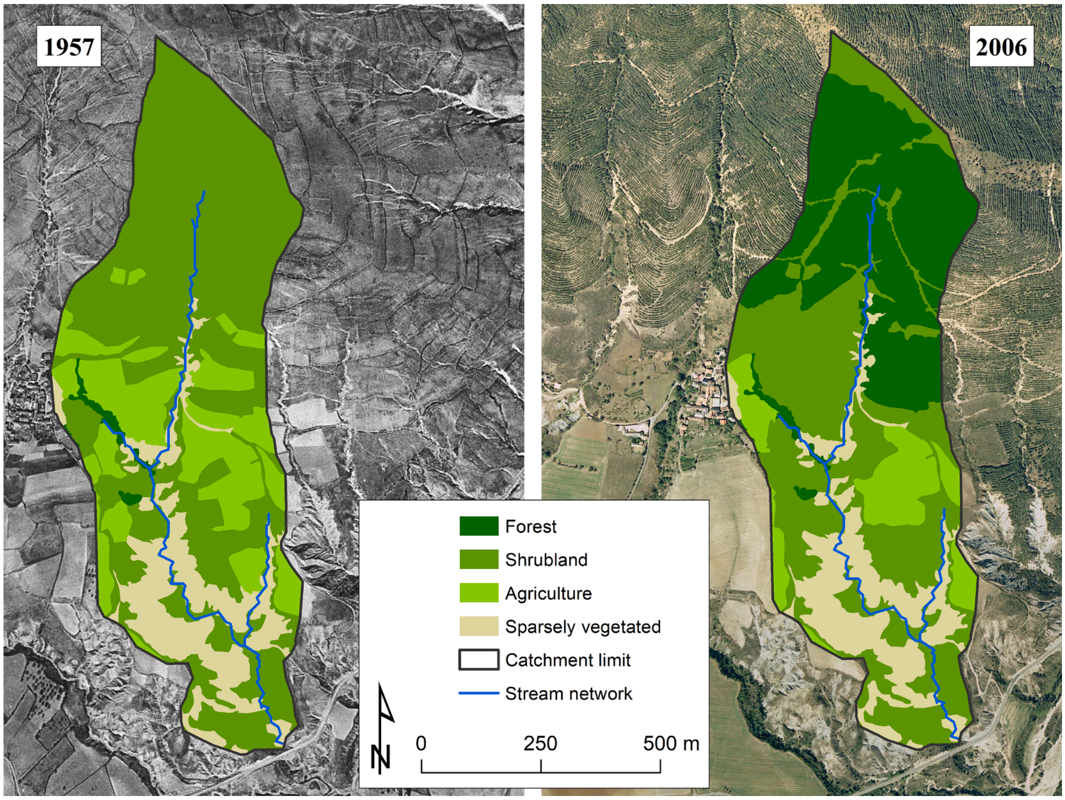

Fig. 2. Land uses and land covers in 1957 (left) and 2018 (right). (i) Forest area is based on afforestation practices carried out during the late 1960ies; (ii) Shrublands as natural revegetation process after land abandonment; (iii) Agriculture was based on cereals in 1957 and grasslands grazed by sheep in 2018; and (iv) Sparsely vegetated areas are related to badlands development.

Table 1
Land use and land cover changes between 1957 and 2018 in the Araguás catchment (Central Spanish Pyrenees) after farmland abandonment. (i) Forest area is based on afforestation practices carried out during the late 1960ies; (ii) Shrublands as natural revegetation process after land abandonment; (iii) Agriculture was based on cereals in 1957 and sheep-grazed grasslands in 2018; and (iv) Sparsely vegetated areas are related to badlands development.

	LULC in 1957 (%)	LULC in 2018 (%)
Agriculture	21.2	9.7
Forest	1.1	33.0
Shrubs	62.0	41.7
Sparsely vegetated	15.7	15.7

significant differences were observed between the mean values of clay and CorgN ratio of afforested and agricultural areas.

No differences were observed for EC values, $CaCO_3$, TN, saturation and wilting points between the different LULC.

Fig. 5 shows the spatial distribution of the interpolated soil properties. Soil properties were highly variable across the catchment with no clear spatial pattern observed for most of the variables. Relatively high clay and silt contents were recorded in the lower part of the catchment, and high sand in the upper part. The spatial pattern of pH was mainly due to its low range of variation; though higher values were observed in the lower part of the catchment related to the presence of Eocene Marls and the development of badland areas (significant differences were recorded, see Fig. 4). EC and $CaCO_3$ did not show any clear distribution

Table 2
Basic statistics of the physico-chemical soil properties in the Araguás catchment including reference sites (n = 9, the whole profile) and sampling points (n = 52, whole profile). SD: Standard deviation, Max: Maximum value, Min: Minimum value, CV: Coefficient of variation.

		Stoniness (%)	Clay (%)	Silt (%)	Sand (%)	pH	EC (μS/cm)	$CaCO_3$ (%)	SIC (%)	SOC (%)	TN (%)	CorgN ratio	BD (g cm^3)	Sat	FC	PWP
Reference sites	Median	24.5	30.6	34.4	26.4	8.4	323.9	32.5	4.2	1.1	0.1	8.4	1.2	0.5	1.2	0.2
	Mean	23.6	31.4	41.2	27.4	8.3	368.6	31.1	3.9	1.6	0.2	9.0	1.2	0.5	1.3	0.2
	SD	15.0	12.8	13.0	9.7	0.2	166.8	8.2	1.0	1.2	0.1	3.0	0.3	0.04	0.4	0.1
	Max	58.7	58.3	63.2	56.8	8.9	1055.0	43.4	5.2	5.7	0.4	18.0	1.8	0.7	2.2	0.3
	Min	0.3	13.5	21.1	13.4	7.7	169.8	6.4	0.9	0.3	0.1	3.9	0.6	0.4	0.6	0.1
	CV	0.6	0.4	0.3	0.4	0.0	0.5	0.3	0.3	0.7	0.4	0.3	0.2	0.1	0.3	0.2
Point samples	Median	20.7	18.8	67.4	13.5	8.4	215.5	40.0	4.8	1.1	0.1	8.3	1.3	0.5	0.9	0.1
	Mean	21.8	18.9	67.1	14.0	8.4	212.4	38.9	4.7	1.1	0.1	8.3	1.3	0.5	0.9	0.2
	SD	7.4	2.7	4.9	6.4	0.1	37.2	7.0	0.8	0.4	0.0	2.1	0.2	0.0	0.1	0.0
	Max	43.3	26.6	75.6	28.8	8.8	295.0	51.8	6.2	2.0	0.3	12.4	1.9	0.5	1.1	0.2
	Min	4.6	13.4	56.5	4.3	8.2	16.3	19.1	2.3	0.4	0.1	4.5	0.8	0.4	0.7	0.1
	CV	0.3	0.1	0.1	0.5	0.0	0.2	0.2	0.2	0.3	0.3	0.3	0.2	0.0	0.1	0.1

Note: EC, electrical conductivity; SIC, soil inorganic carbon; SOC, soil organic carbon; TN, total nitrogen; CorgN ratio, carbon and nitrogen ratio; BD, bulk density; Sat, saturation point; FC, field capacity; PWP, permanent wilting point.

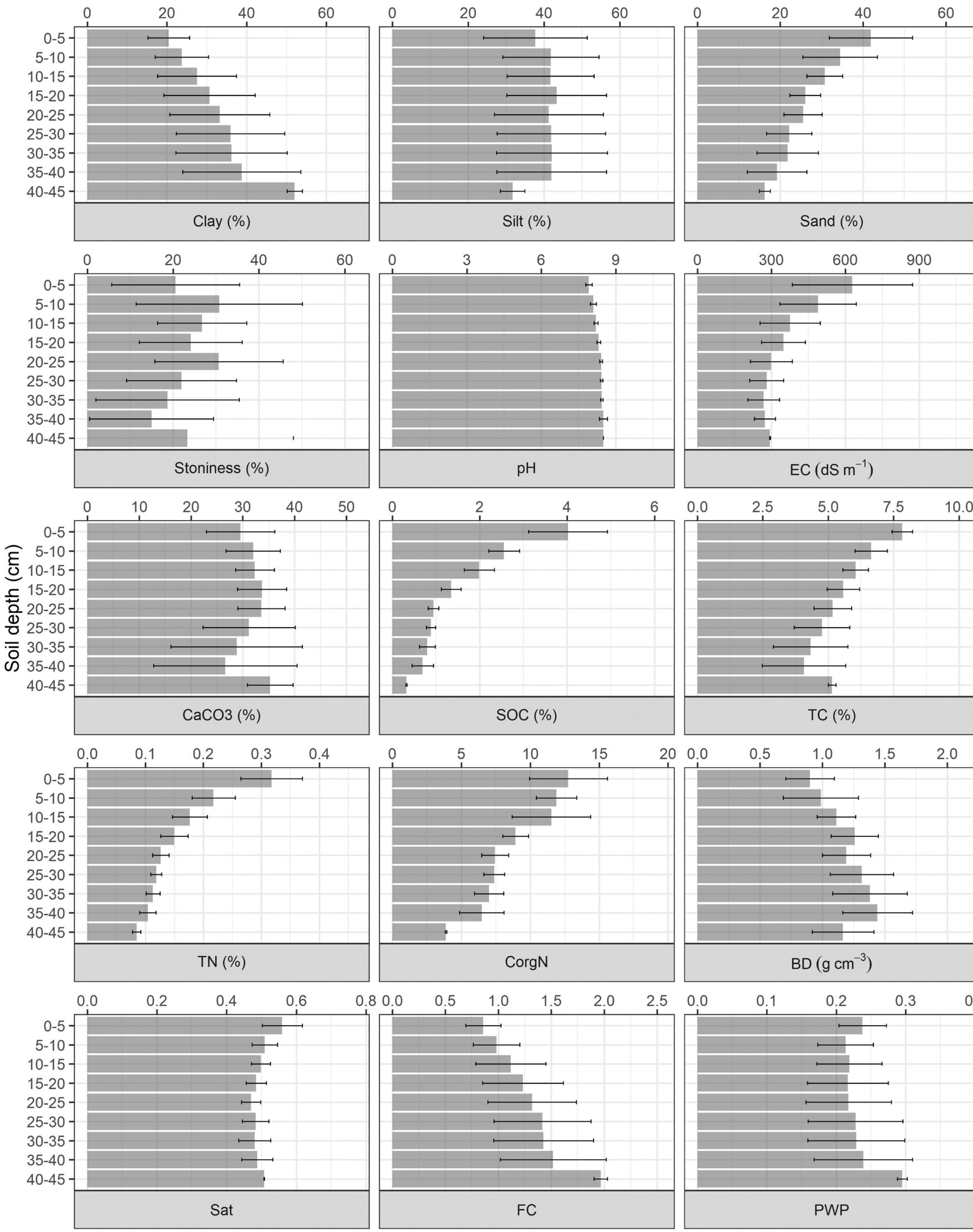

Fig. 3. Depth distribution of physico-chemical properties in the soil reference profiles (n = 9). Error bars represent the standard deviation. Note: EC, electrical conductivity; SOC, soil organic carbon; TC, total carbon; TN, total nitrogen; CorgN ratio, carbon and nitrogen ratio; BD, bulk density; Sat, saturation point; FC, field capacity; PWP, permanent wilting point.

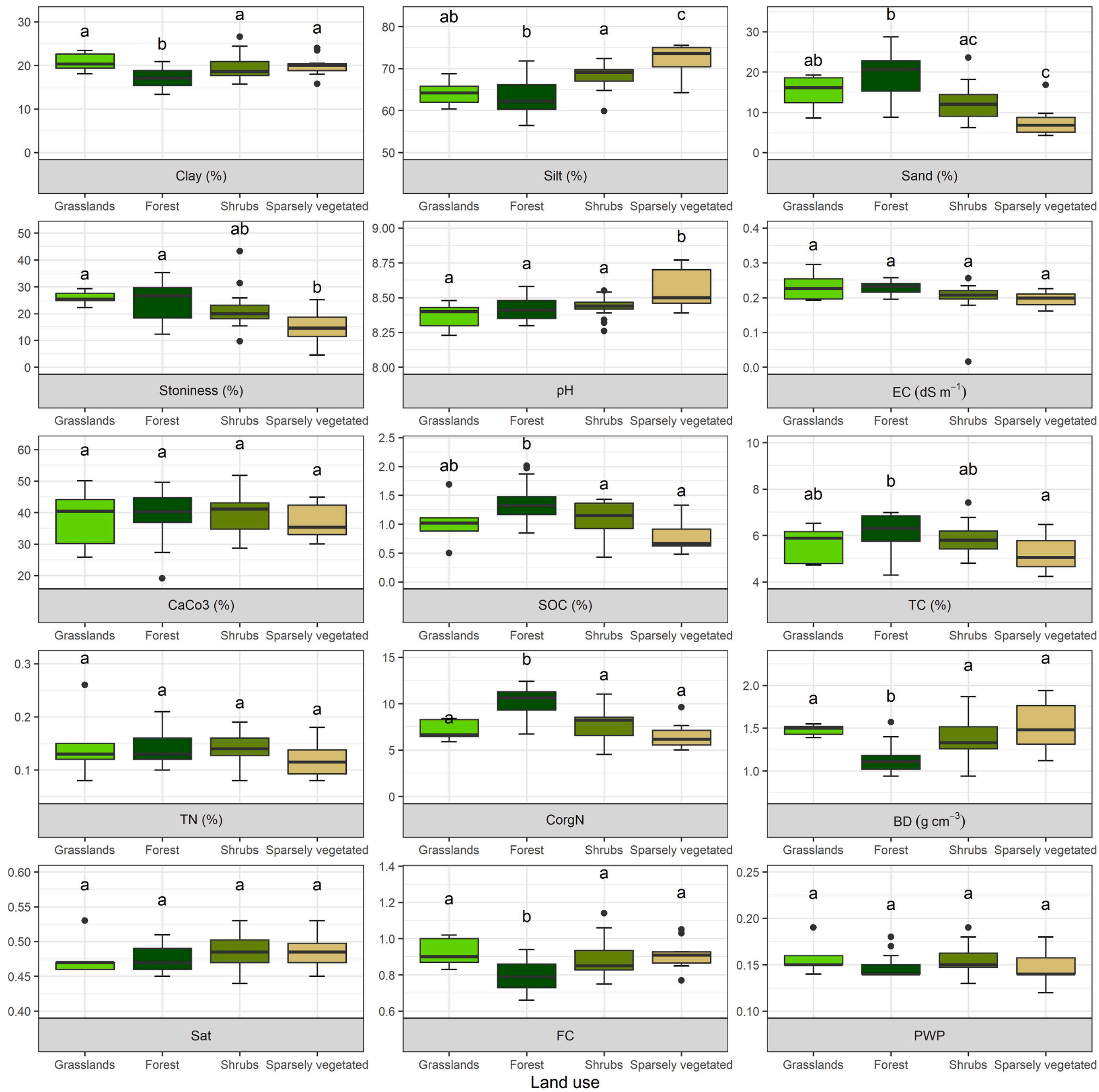

Fig. 4. Boxplot of main physico-chemical soil properties and nutrient contents in the different land use and land covers sites. Note: EC, electrical conductivity; SOC, soil organic carbon; TC, total carbon; TN, total nitrogen; CorgN ratio, carbon and nitrogen ratio; BD, bulk density; Sat, saturation point; FC, field capacity; PWP, permanent wilting point. Note: significant differences were indicating with different lower case letters (level of significance ($p < 0.05$).

pattern in the catchment. High SOC, TC, TN were found at the upper part of the catchment, related to the presence of the afforested areas; while lower values were found in the lower part of the catchment, close to the main gully, linked to the presence of sparsely vegetated areas and badlands. The distribution of the edaphic properties is mainly determined by clay and SOC distribution however it doesn't exhibit a clear spatial pattern. High spatial variation was displayed and higher values were recorded in the middle part of the catchment.

3.4. Relationship between nutrients and soil properties

Table 4 shows the correlations between all physico-chemical soil properties and nutrients. SOC content was directly correlated with sand, EC, TN, CorgN ratio and saturation and wilting point, and inversely correlated with silt, pH, $CaCO_3$ and bulk density. Similar patterns to SOC values were observed with TN.

Table 5 shows the correlation between nutrients and soil properties for afforestation and shrubland sites. In afforested areas, SOC content was directly correlated with sand, EC, TN, and wilting point, and inversely correlated with silt, pH and $CaCO_3$. In shrubland areas, SOC content was directly correlated with EC, TN, CorgN ratio and saturation and wilting point and inversely correlated with $CaCO_3$ content. The main discrepancy between both land uses was the lack of correlation between nutrients and particle size fractions in shrubland areas.

3.5. SOC content and density fractionation

The average SOC content in the reference sites considering the complete soil profile was 1.6%. Mean total SOC content in the catchment was 1.1% and contents in the different LULC were 1.4% in afforested

Table 3
Basic statistics of the physico-chemical properties of the sampling points under the different land uses and land covers in the Araguás catchment (n = 52, whole profile). SD: Standard deviation, Max: Maximum value, Min: Minimum value, CV: Coefficient of variation.

		Stoniness (%)	Clay (%)	Silt (%)	Sand (%)	pH	EC (μS/cm)	$CaCO_3$ (%)	SOC (%)	TN (%)	CorgN ratio	BD (g cm^3)	Sat.	FC	PWP
Grasslands	Median	25.4	20.3	64.2	16.1	8.4	226.2	40.5	1.0	0.1	6.7	1.5	0.5	0.9	0.2
n = 5	Mean	25.9	20.8	64.2	15.0	8.4	233.1	38.1	1.0	0.1	7.1	1.5	0.5	0.9	0.2
	SD	2.7	2.2	3.3	4.5	0.1	42.5	10.0	0.4	0.1	1.1	0.1	0.0	0.1	0.0
	Max	29.3	23.4	68.8	19.3	8.5	295.0	50.1	1.7	0.3	8.4	1.6	0.5	1.0	0.2
	Min	22.3	18.1	60.4	8.6	8.2	193.3	25.9	0.5	0.1	5.9	1.4	0.5	0.8	0.1
	CV	0.1	0.1	0.1	0.3	0.0	0.2	0.3	0.4	0.5	0.2	0.0	0.1	0.1	0.1
Afforestation	Median	24.3	17.5	64.0	20.6	8.4	231.6	41.7	1.3	0.1	10.7	1.1	0.5	0.8	0.1
n = 17	Mean	24.0	17.1	64.0	18.9	8.4	227.5	39.8	1.4	0.1	10.3	1.1	0.5	0.8	0.1
	SD	7.1	2.2	4.9	6.1	0.1	19.1	7.9	0.3	0.0	1.5	0.2	0.0	0.1	0.0
	Max	35.3	20.9	72.4	28.8	8.6	257.0	49.6	2.0	0.2	12.4	1.6	0.5	0.9	0.2
	Min	12.3	13.4	56.5	8.8	8.3	195.8	19.1	0.8	0.1	6.7	0.9	0.4	0.7	0.1
	CV	0.3	0.1	0.1	0.3	0.0	0.1	0.2	0.2	0.2	0.2	0.1	0.0	0.1	0.1
Shrublands	Median	19.9	18.6	68.4	12.9	8.4	212.2	39.7	1.2	0.1	8.2	1.3	0.5	0.8	0.1
n = 20	Mean	22.1	19.5	67.8	12.7	8.4	202.3	39.2	1.1	0.1	7.7	1.4	0.5	0.9	0.2
	SD	7.3	2.8	3.0	4.8	0.1	47.5	6.1	0.3	0.0	1.8	0.2	0.0	0.1	0.0
	Max	43.3	26.6	71.9	23.6	8.6	255.9	51.8	1.4	0.2	11.0	1.9	0.5	1.1	0.2
	Min	9.7	15.7	59.9	6.2	8.3	16.3	28.8	0.4	0.1	4.5	0.9	0.4	0.7	0.1
	CV	0.3	0.1	0.0	0.4	0.0	0.2	0.2	0.3	0.2	0.2	0.2	0.1	0.1	0.1
Sparsely vegetated	Median	14.6	20.0	73.6	6.8	8.5	199.1	35.4	0.7	0.1	6.2	1.5	0.5	0.9	0.1
badlands areas	Mean	15.4	20.0	72.4	7.6	8.6	196.3	36.9	0.8	0.1	6.5	1.5	0.5	0.9	0.1
n = 10	SD	6.2	2.4	3.6	3.7	0.1	21.5	5.8	0.3	0.0	1.4	0.3	0.0	0.1	0.0
	Max	25.2	24.0	75.6	16.8	8.8	226.1	44.9	1.3	0.2	9.6	1.9	0.5	1.1	0.2
	Min	4.6	15.8	64.3	4.3	8.4	161.3	30.1	0.5	0.1	5.0	1.1	0.4	0.8	0.1
	CV	0.4	0.1	0.1	0.5	0.0	0.1	0.2	0.4	0.3	0.2	0.2	0.0	0.1	0.1

Note: EC, electrical conductivity; SIC, soil inorganic carbon; SOC, soil organic carbon; TN, total nitrogen; CorgN ratio, carbon and nitrogen ratio; BD, bulk density; Sat, saturation point; FC, field capacity; PWP, permanent wilting point.

sites, 1.1% in shrublands and grasslands, and 0.8% in sparsely vegetated badland areas.

Related to soil fractions, the average recovery of soil mass after density fractionation was 99.83 ± 1.13%, and FLF and OLF represented a small percentage of the soil mass in the different LULC (Table 6). In all the cases, SOC content was similar in FLF and OLF, being in both cases higher than in HF. FLF and OLF had SOC contents always higher than 14% while the HF contained only a small percentage of SOC, always lower than 2.9%.

Significant differences were only found in FLF and OLF fractions. In FLF and OLF, SOC contents in afforested sites were higher than in grasslands and sparsely vegetated areas. Differences were also observed between grasslands and shrublands. No differences were observed for HF between LULC (Fig. 6).

Also, significant differences were recorded for the mass of density fractions between different LULC. In all the LULC, the HF represented the most important part of the total SOC (Table 6). The contribution of the HF to SOC was slightly lower in the afforested sites (41.9%) while the FLF was higher in these sites (29.6%) (Table 6). A high contribution of HF to SOC is also recorded in grassland sites (Table 6).

CorgN ratios were higher in FLF and OLF compared to the ones recorded in HF, as both fractions are mainly composed of almost pure organic carbon (Fig. 6). Significant higher CorgN values were recorded in afforested sites (similar to the values recorded in the sparsely vegetated sites) compared to shrubland and grassland sites, suggesting lower quality of the organic matter. Contrarily, lower CorgN ratios in HF in shrubland and grassland sites can be related to an increase of the quality of the OM.

4. Discussion

4.1. LULCC and physico-chemical soil characteristics

The comparison between LULC of 1956 and 2018 in the Araguás catchment showed a sharp increase of forest area (from 1.1% to 33.0%) due to human intervention and afforestation practices at the expense of shrubland and agriculture sites: shrubland was in 1956 the most extensive LULC occupying about 62.0% of the area, while agriculture represented about 21.2%. Farmland abandonment involves a process of vegetation succession with different temporal phases: herbaceous cover, shrubs, cleared forest and dense forest (García-Ruiz and Lana-Renault, 2011). This process determines changes in landscape structure from a mosaic landscape, with a high degree of diversity and a high number of patches to a more homogeneous landscape, in which natural features dominate (Antrop, 2005; Lasanta-Martínez et al., 2005; Palang et al., 2005; Agnoletti, 2014). However, post abandonment management practices after farmland abandonment (i.e. natural revegetation, afforestation, shrubland clearing, pasture establishment) can introduce significant changes in landscape structure and quality, and land degradation (using soil quality and SOC stocks as main indicators), soil erosion and water resources.

Revegetation processes (natural or human-induced) after farmland abandonment is a worldwide phenomenon (i.e. Sluis et al., 2014; Castro et al., 2020; Yin et al., 2020). Different studies in Mediterranean mountain areas suggested that these LULCC affect ecosystem services, such as quantity and quality of water resources (García-Ruiz et al., 2011), pastoral resources (e.g., Gartzia et al., 2016; Lasanta et al., 2016), and soil quality, soil conservation and soil carbon sequestration (i.e., Navas et al., 2008; De Baets et al., 2013; Boix-Fayos et al., 2020).

Significant differences were observed between reference sites (non-disturbed) and catchment/grid points. Reference sites present higher nutrients contents (SOC, TN), CorgN ratios and sand and silt contents, than grid points. The results, observed in the Araguás catchment, indicated that farmland abandonment and the legacy of the historic LULCC after farmland abandonment is one of the principal factors affecting the variation of physico-chemical soil properties, as has been demonstrated in other studies worldwide (Zornoza et al., 2009; Cuesta et al., 2012; Yaşar Korkanç, 2014; Nadal-Romero et al., 2016; Lizaga et al., 2019; Sciubba et al., 2021).

According to the interpolation analysis and the spatial distribution of the physical and chemical soil properties there is a large variation across the Araguás catchment. Significant differences have been observed

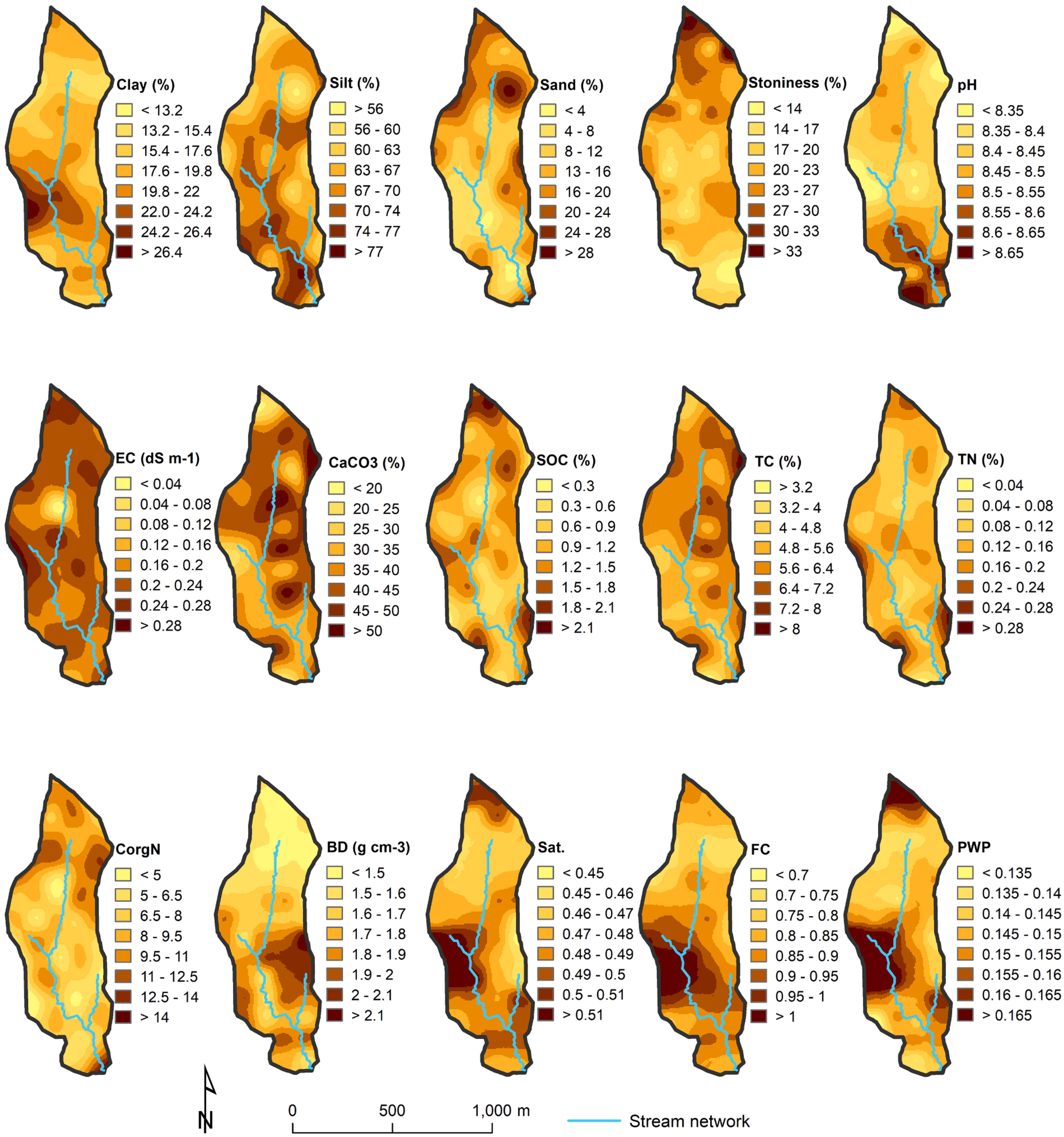

Fig. 5. Spatial distribution of the soil properties in the Araguás catchment. Note: EC, electrical conductivity; SOC, soil organic carbon; TC, total carbon; TN, total nitrogen; CorgN ratio, carbon and nitrogen ratio; BD, bulk density; Sat, saturation point; FC, field capacity; PWP, wilting point.

under the different LULC. Variations in pH are probably due to the LULCC and the distribution of the parent material (Catoni et al., 2016; Company et al., 2022). The high pH of the soils is due to the dominance of alkaline parent material (Eocene marls and Eocene flysch), with high presence of carbonates (mean value around 39%). Afforestation generated a greater accumulation of litter in the top soil that could contribute to significant decrease in soil pH due to the acidifying effect of pine litter (Iovieno et al., 2010). Contrary, higher pH values were recorded in sparsely vegetated badland areas, linked to badlands occurrence and the presence of Eocene marls in the lower part of the catchment.

Although scientific literature suggests that soil texture and particle size distribution are less dynamics (i.e., Gaspar and Navas, 2013), some changes may occur due to anthropogenic activities, LULCC and post-land abandonment management practices. Our results showed significant differences between afforested sites (higher sand contents) and shrubland and sparsely vegetated areas related to soil texture (higher silt contents). Different authors also suggested the influence of the parent material on soil texture, which can be also related to the SOC contents (Company et al., 2022). So, the possible influence of parent material should not be discarded (Eocene flysch in the upper part and Eocene marls in the lower part of the catchment) and further studies should be focussed in the evaluation of parent material after land abandonment and revegetation processes and management practices. No differences were observed between LULC for saturation and wilting point contents related to the relative homogeneous textures of the soil of the catchment. However, lower field capacity values were recorded in the afforested areas, related to the low clay and silt contents and the high sand and organic carbon contents.

Afforestation and natural revegetation (i.e. shrublands) after farmland abandonment are different strategies to restore soil properties, soil

Table 4
Correlation coefficients among physico-chemical properties for all land use and depths.

	Stoniness	Clay	Silt	Sand	pH	EC	$CaCO_3$	SOC	TN	CorgN	BD	Sat	FC
Clay	−0.208												
Silt	***−0.545***	***0.368***											
Sand	***0.503***	***−0.708***	***−0.917***										
pH	***−0.396***	−0.016	***0.578***	***−0.432***									
EC	0.249	0.056	***−0.513***	***0.366***	***−0.547***								
$CaCO_3$	−0.037	*−0.307*	0.084	0.067	0.002	***−0.373***							
SOC	0.211	−0.217	***−0.577***	***0.532***	***−0.554***	***0.645***	***−0.376***						
TN	0.099	0.129	**−0.328**	0.194	**−0.531**	***0.543***	***−0.401***	***0.693***					
CorgN	0.164	***−0.431***	***−0.464***	***0.536***	−0.266	***0.410***	−0.073	***0.716***	0.018				
BD	−0.602	***0.388***	***0.418***	***−0.484***	0.226	−0.232	0.081	***−0.433***	0.012	***−0.586***			
Sat	**−0.278**	***0.660***	**0.333**	***−0.535***	−0.151	**0.299**	***−0.485***	***0.413***	***0.508***	0.090	0.110		
FC	−0.253	***0.996***	***0.450***	***−0.768***	0.040	0.004	**−0.286**	−0.264	0.092	***−0.459***	***0.414***	***0.666***	
PWP	−0.041	***0.741***	−0.071	−0.263	***−0.396***	***0.496***	***−0.533***	***0.494***	***0.589***	0.109	0.048	***0.870***	***0.705***

Bold numbers indicate statistical significance at $p \leq 0.05$ level. Bold and italicized numbers indicate statistical significance at $p \leq 0.01$.
Note: EC, electrical conductivity; SOC, soil organic carbon content; TN, total nitrogen content; CorgN, ratio organic carbon and nitrogen; BD, bulk density; Sat., Saturation capacity; FC, field capacity; PWP, permanent wilting point.

quality and soil conservation. Mean contents of clay, silt, sand, SOC, CorgN ratio, bulk density and field capacity were significantly different in the afforested sites compared to shrubland sites related mainly to parent material (i.e. grain size) and LULC (i.e. nutrient contents). For instance, De Marco et al. (2022) and Cuesta et al. (2012) indicated that afforestation practices can accelerate the recovery of some soil properties of abandoned farmland in comparison with secondary succession, but these effects are noticeable at long-term scale.

Bulk density decreased in afforested sites related to the higher above, as well as belowground biomass production. Indeed, a strong negative correlation have been observed between bulk density values and soil organic carbon. Also, grain size distribution presents a significant correlation with bulk density values (positive with silt and clay, and negative with sands). Similar results have been reported in previous studies (i.e. Alawamy et al., 2022). High bulk density values (as the one recorded in grassland and shrubland sites), may be related to both past and present agricultural practices and grazing activities, triggering soil compaction and limiting root extension.

Contrary, CorgN ratios were higher in afforested sites. Similar results have been reported by many authors after afforestation with conifers (Martín-Peinado et al., 2016; Segura et al., 2020). These authors suggested that CorgN increases could be related to gradual inputs from litter fall, and their low decomposition rates, which would also support a higher stability of SOC (Cunningham et al., 2015). A positive and significant correlation between CorgN and SOC contents found in the Araguás catchment (considering only shrublands) indicates that the accumulation rate of organic carbon is higher than nitrogen accumulation after farmland abandonment and LULCC.

4.2. Soil organic carbon and density fractionation

The effects of LULCC and afforestation on SOC contents and stocks have been synthesized worldwide by Post and Kwon (2000), Guo and Gifford (2002), Paul et al. (2002) and Li et al. (2012). Likewise, scientific literature discussed the effects of land abandonment and revegetation processes in Mediterranean mountain areas on SOC contents and stocks, showing contrasting results, with increases, decreases or not changes after farmland abandonment (Muñoz-Rojas et al., 2011; Gabarrón-Galeote et al., 2015; Rodríguez-Martín et al., 2016; Djuma et al., 2020; Bell et al., 2021; Nadal-Romero et al., 2021). Likewise, similar results were found in other studies worldwide. Reichert et al. (2022) in Southern Brazil concluded that land abandonment and natural revegetation increased soil organic matter, nutrients and microbial activity. Besides, Wertebach et al. (2017) found significant differences in SOC values after land abandonment, limited to the topsoil (0–5 cm). In all cases, SOC increased significantly with time since abandonment. Contrarily, Contreras-Cisneros et al. (2022) indicated that SOC tended to decrease as years of abandonment increase, suggesting that SOC accumulation after farmland abandonment through unmanaged succession is difficult to achieve.

The results recorded in the Araguás catchment confirm that afforestation induced profound changes in soil characteristics and soil organic carbon contents. Afforestation with conifers has positive effects on SOC and TN contents, favouring forest floor development due to the input of aboveground and belowground tree litter. Conifer litter decomposes more slowly (low-litter quality of pines comparing with herbaceous understory biomass) and there is a greater build-up of conifer litter and a different distribution of SOC and TN along the soil profile (Rumpel and Kögel-Knabner, 2011; Segura et al., 2020). Higher SOC contents in pine afforested areas can also be due to the higher density of the vegetation cover. Studies in Pyrenean abandoned fields have shown significant differences in SOC and TN contents along with changes in other general soil properties in function of the age of abandonment (Navas et al., 2012). This was attributed to the effect of natural revegetation on soil recovery for longer periods of land abandonment.

Lower SOC contents were recorded in shrubland and sparsely vegetated badland areas. In the case of shrublands, the low SOC content is related to the less mature plants. Likewise, in shrubland sites, the lower mass and turnover of fine roots can also prevent the decomposition of SOM and reduce SOC stocks.

In agreement with our findings, other studies have indicated the relevant role of grasslands for enhancing accumulation of soil organic carbon, in some cases at similar levels compared to forest (Post and Kwon, 2000; Jackson et al., 2002; Wei et al., 2012). In that sense, Boix-Fayos et al. (2009) indicated that SOC concentrations in pasturelands do not often differ significantly from those found in Mediterranean forest. Our results show that no significant differences were observed between grassland and afforested sites related to SOC values. In that sense, different authors suggested that the conservation of grassland ecosystem is important for preserving the ecosystem services they provided such as sequestration of CO_2 (Castillo-Garcia et al., 2022) and suggest that pasture establishment on abandoned farmland sites is one of the alternatives that may help to restore soil conditions.

Significant correlations were observed between SOC and TN contents, although no significant differences were observed related to TN between different LULC, remaining stable over the time of abandonment and different management. This relationship suggests a similar pathway of both nutrients. Several authors have reported no differences between LULC related to TN. For instance, Lizaga et al. (2019) suggested that natural revegetation boosted TN and no differences were observed between natural revegetation and afforestation sites.

Likewise, the biogeochemical cycles of carbon fractions are strongly influenced by LULC. FLF (influenced by plant residue inputs that are easily decomposed) is easily affected by LULCC and land management,

Table 5
Correlation coefficients among physico-chemical properties. The upper triangle (yellow) shows the correlation values for the shrubland samples (n = 20) and the lower triangle (green) shows the correlation values for the afforested samples (n = 17).

	Stoniness	Clay	Silt	Sand	pH	EC	$CaCO_3$	SOC	TN	CorgN	BD	Sat	FC	PWP
Stoniness		−0.332	−0.254	0.329	−0.108	−0.009	0.085	−0.180	−0.357	0.056	**−0.613**	-0.0360	−0.341	−0.325
Clay	0.046		0.463	***−0.778***	**0.566**	0.295	**−0.601**	0.370	0.513	−0.012	0.159	***0.871***	***0.997***	***0.885***
Silt	**−0.545**	0.423		***−0.917***	−0.085	−0.372	−0.034	−0.249	−0.246	−0.197	−0.205	0.462	0.530	0.197
Sand	***0.417***	***−0.693***	***−0.946***		0.315	0.131	0.295	0.010	−0.056	0.145	0.074	***−0.719***	***−0.824***	***−0.538***
pH	−0.468	0.270	0.432	−0.440		**−0.628**	0.316	−0.501	**−0.650**	−0.136	−0.088	**−0.600**	−0.550	**−0.654**
EC	**0.573**	−0.188	***−0.742***	***0.657***	**−0.544**		**−0.555**	**0.791**	***0.730***	0.550	0.000	0.468	0.250	**0.603**
$CaCO_3$	−0.404	−0.193	**−0.545**	−0.364	0.385	***−0.632***		**−0.585**	−0.336	−0.505	0.196	**−0.646**	***−0.577***	***−0.713***
SOC	0.343	−0.289	**−0.546**	**0.538**	**−0.535**	***0.690***	***−0.622***		***0.766***	***0.776***	0.039	**0.680**	0.334	***0.760***
TN	0.376	0.003	−0.413	0.328	**−0.485**	***0.641***	***−0.685***	***0.794***		0.250	0.442	**0.603**	0.470	***0.747***
CorgN	0.011	−0.479	−0.237	0.360	−0.160	0.307	−0.044	0.459	−0.167		−0.345	0.390	−0.028	0.376
BD	***−0.780***	0.045	**0.561**	−0.462	0.274	***−0.651***	0.354	−0.338	−0.376	−0.052		0.008	0.136	0.136
Sat	−0.047	**0.602**	0.446	**−0.570**	−0.034	0.074	−0.302	0.370	0.440	−0.017	0.115		***0.873***	***0.9949***
FC	−0.021	***0.994***	**0.517**	***−0.766***	0.306	−0.265	−0.118	−0.337	−0.046	−0.480	0.109	***0.621***		**0.864**
PWP	0.300	***0.672***	−0.045	−0.204	−0.168	0.429	***−0.656***	**0.514**	***0.621***	−0.082	−0.221	***0.824***	***0.630***	

Bold numbers indicate statistical significance at $p \leq 0.05$ level. Bold and italicized numbers indicate statistical significance at $p \leq 0.01$.
Note: EC, electrical conductivity; SOC, soil organic carbon content; TN, total nitrogen content; CorgN, ratio organic carbon and nitrogen; BD, bulk density; Sat., Saturation capacity; FC, field capacity; PWP, permanent wilting point.

and this fraction can be considered a sensitive indicator for evaluating changes in SOC as was already suggested by Sainepo et al. (2018) and Gaspar et al. (2019). In grassland samples, the relative contribution of FLF and OLF is lower than in the other LULC, especially compared with afforested samples. Higher FLF values were found in afforested sites, due to high litter input and also high CorgN ratios in coniferous forest. HF is the main pool of SOC for all LULC having grassland the highest HF pool (63.2%) and the afforested sites the lowest (30.6%), and no differences were observed between LULCC, similar to other results, indicating that remained stable over time. The high HF values in grassland sites might be related to belowground carbon input by grassland species, that contribute to more stable fractions due to root exudation and microbial secretion (Malhotra et al., 2018; Sanderman et al., 2021; Li et al., 2022). Trigalet et al. (2016) suggested that labile fractions gradually increased after land abandonment, indicating a high sensitivity of the fraction to the carbon input changes. Our results showed a higher SOC content in afforested sites, that can be related to the larger labile forms (FLF and OLF). However, SOC accumulation in labile forms in afforested sites could hinder the feasibility of coniferous afforestation to restore degraded soils and enhance soil quality. Instead, grassland can be found as a suitable alternative able to increase SOC content, and stabilize SOC.

We focus only on the top soil layer, as it is accepted to be the most sensitive layer. However, Poeplau and Don (2013) carried out a global analysis across Europe including subsoil samples and similar results were found. In that sense, we consider that further research focused on subsoil should be carried out, although density fractionation is a time-consuming laboratory practice. In that sense, novel techniques, such as spectroscopy could help to solve this time limitation and research gap (see Jaconi et al., 2019; Angelopoulou et al., 2020, 2019).

This study has demonstrated that land use and land cover changes exert an important control on physico-chemical soil properties and nutrients in Mediterranean mountain areas. The responses after farmland abandonment are strongly variable and it is still a controversial issue in the scientific literature. In that sense, the results obtained in the Araguás catchment are due to a long history of human intervention through cultivation in steep slopes and afforestation programmes. In addition, the extrapolation of the results at catchment scale (small catchment with different contrasted land uses) is complex, but allow us to obtain a new and better understanding of the spatial extent and the differences between afforestation and revegetation in equal geographical conditions.

One of the main difficulties was founding for locations for the reference sites (undisturbed vegetated areas). This issue has been already noted by different authors, such as Parson and Foster (2011) that questioned the assumption of the representativeness of the reference sites and its conservative behaviour. To overcome this limitation, a careful planning, a detailed soil sampling, expert knowledge of the study area and robust statistical analysis are determinant.

Assessing LULCC is critical for understanding future challenges in land management and climate change adaptation measures in Mediterranean mountain areas. In that sense, scientific studies and stakeholders should be taken into account to decide what is the best post-land use management practices after farmland abandonment.

5. Conclusion

Identifying and monitoring land use and land cover changes, and understanding their impacts in soil physico-chemical properties is critical to improve the sustainability of soil and land management after farmland abandonment. The main objective of this study was to provide insights into the effects of farmland abandonment and post-land abandonment management practices (i.e. natural revegetation, afforestation) on soil physico-chemical properties and soil organic carbon dynamics, in a small representative Mediterranean mountain catchment.

This study confirms that LULCC is one of the principal factors affecting the variation of physico-chemical soil properties, together with parent material. In general, significant differences between LULC have

Table 6
Density fractionation results: soil recovery per fraction, SOC (Soil Organic Carbon) per fraction and contribution (%) of the different fractions to total SOC in the different LULC.

	Soil recovery (%)				SOC (mg g^{-1})			Recovery % SOC		
	FLF	OLF	HF	Total	FLF	OLF	HF	FLF	OLF	HF
Grasslands (n = 5)	1.59	1.69	96.89	*100.0*	23.68	33.59	1.62	15.76	21.00	63.20
Afforestation (n = 10)	3.59	3.25	93.18	*100.0*	32.35	39.91	1.68	29.62	28.47	41.92
Shrublands (n = 12)	2.87	2.50	94.58	*99.9*	29.63	37.80	1.89	24.10	27.11	48.79
Sparsely vegetated areas (n = 5)	2.50	1.79	94.55	*98.8*	38.04	36.81	1.35	27.26	25.98	46.77

Note: FLF: Free Light Fraction; OLF: Occluded Light Fraction; HF: Heavy Fraction.

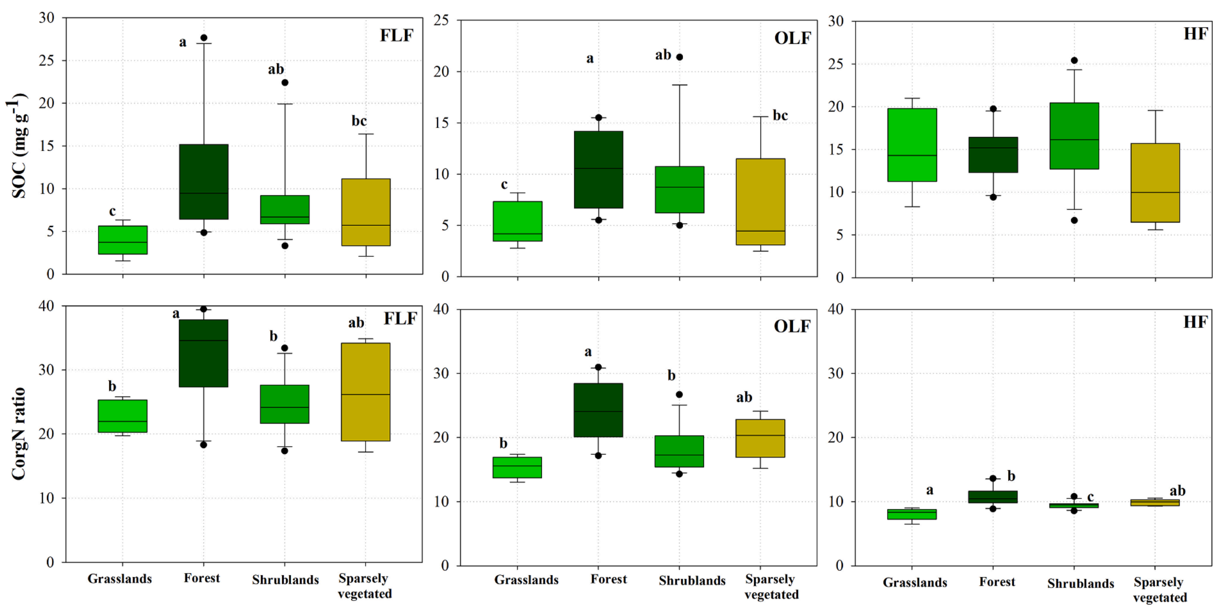

Fig. 6. Soil organic carbon (SOC) and CorgN ratios in the three different density fractions. Note: FLF: Free Light Fraction; OLF: Occluded Light Fraction; HF: Heavy Fraction. Significant differences were indicating with different lower case letters (level of significance ($p < 0.05$).

been found related to soil texture, stoniness, pH, soil organic carbon, total carbon, CorgN ratio, bulk density and field capacity. Differences between afforested and shrublands were detected for few parameters; higher values were recorded in afforested sites for clay and silt and soil organic carbon contents, CorgN ratio, bulk density and field capacity. Significant differences related to SOC content between shrubland and afforested sites suggest that soil organic carbon only increase slowly after the termination of agricultural activities, and that in the short term, afforestation produces a faster increase in SOC than natural revegetation process (1.4 and 1.1%, respectively). However, no differences were observed in the total nitrogen contents (0.1% in both cases).

In addition, the significant role of grassland in enhancing the accumulation of soil organic carbon has been proved. Likewise, the relative contribution of each of the organic carbon fractions to the bulk soil organic carbon showed differences between LULC. The amount of FLF and OLF is significantly higher in afforested (58.1%) and shrubland sites (51.2%) than in grassland sites (36.8%), suggesting that grassland species contribute to SOC stabilization in the stable fraction.

Further research should be carried out to understand the role of soil redistribution processes on nutrient stocks (SOC and TN) and to discern the effects of parent material and other different post-land management practices after land abandonment in Mediterranean mountain areas.

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.

Data availability

Data will be made available on request.

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