Searching for the best post-land abandonment management to enhance long-term carbon storage in Mediterranean mountain areas

Cortijos-López, M.; Lasanta, T.; Cammeraat, E.; Nadal-Romero, E.

DOI
10.1016/j.geosus.2025.100265

Publication date
2025

Document Version
Final published version

Published in
Geography and Sustainability

Geography and Sustainability 6 (2025) 100265

Contents lists available at ScienceDirect

Geography and Sustainability

journal homepage: www.elsevier.com/locate/geosus

Research Article

Searching for the best post-land abandonment management to enhance long-term carbon storage in Mediterranean mountain areas

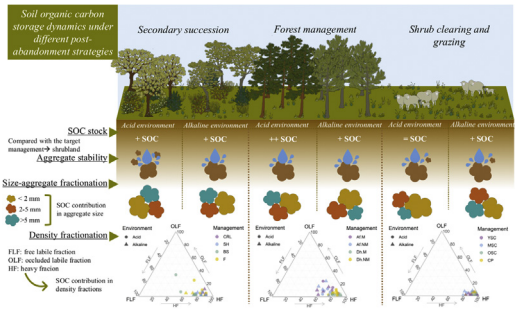
Melani Cortijos-López[a,*], Teodoro Lasanta[a], Erik Cammeraat[b], Estela Nadal-Romero[a]

[a] Instituto Pirenaico de Ecología, Consejo Superior de Investigaciones Científicas (IPE-CSIC); Campus de Aula Dei, Zaragoza 50059, Spain
[b] Ecosystem & Landscape Dynamics (IBED-ELD), Institute for Biodiversity and Ecosystem Dynamics, University of Amsterdam, Amsterdam 1090GE, the Netherlands

HIGHLIGHTS

- Land management through shrub clearing and forest management enhances SOC stocks.
- Shrub clearing increases microaggregates and their SOC contribution in acid soils.
- Aggregate stability improves with afforestation (acid) and all strategies (alkaline).
- Shrub clearing enhances recalcitrant carbon in alkaline and acid environments.
- Benefits of post-abandonment land management are evidenced in carbon storage.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 15 July 2024
Received in revised form 12 December 2024
Accepted 16 December 2024
Available online 10 January 2025

Keywords:
Mediterranean mountain
Soil organic carbon
Afforestation
Pastures
Natural revegetation

ABSTRACT

The abandonment of rural activities in the Mediterranean mid-mountains has led to the activation of revegetation processes, as well as the subsequent implementation of various management measures to mitigate the associated ecosystem disservices. Focusing on soil environment and its growing importance in a climate change scenario, it is of great interest to study how land management and landscape changes can affect, not only the soil carbon storage process, but also its dynamics. A study was conducted in La Rioja (Iberian System, Spain), comparing three post-abandonment management strategies: secondary succession, forest management, and shrub clearing and extensive grazing. These strategies were analysed in two types of soil environments (acid and alkaline) and for two depth ranges (0–20 cm and 20–40 cm). Laboratory analyses were performed on aggregate stability and soil organic carbon fractionation with regard to three aggregate sizes (< 2 mm, 2–5 mm, > 5 mm) and three density fractions (free labile, occluded, and heavy fraction). The results showed that: 1) SOC content in aggregates < 2 mm (relative to total SOC) increases with shrub clearing and grazing strategy in acid environments; 2) aggregate stability benefits from the implementation of afforestation in acid environments and from all three study strategies in alkaline ones; 3) in acid environments, the percentage of labile fractions (free and occluded) in afforested sites is significantly higher compared with shrubland, while in alkaline environments, recalcitrant SOC is significantly higher in shrub clearing sites. Thus, land management should be focused on SOC storage after land abandonment in Mediterranean mountainous environments.

1. Introduction

Mediterranean mountains serve as a crucial reserve for resources and ecosystem services for human societies (Bernués et al., 2014; Keesstra et al., 2018). As a result of rural exodus, they have been suffering from abandonment since the mid-20th century, which has triggered slow natural revegetation processes in marginalized areas (Lasanta-Martínez et al., 2005; Pueyo and Beguería, 2007). The prevalent trend of shrub encroachment on abandoned fields brings both ecosystem benefits (i.e., the recovery of natural systems and a reduction in erosion risk) and drawbacks (i.e., a decrease in water and agro-pastoral resources,

* Corresponding author.
E-mail address: melani@ipe.csic.es (M. Cortijos-López).

https://doi.org/10.1016/j.geosus.2025.100265

or an increasing risk of wildfires) (García-Ruiz and Lana-Renault, 2011; Lasanta, 2019; Khorchani et al., 2021). Faced with this positive-negative balance, public administrations have implemented a series of management measures that have significantly contributed to landscape evolution, as well as land use and land cover (LULC) changes in recent years. Afforestation programs with *coniferous* species have been conducted by national forest services throughout the Mediterranean region (i.e., Ortigosa et al., 1990; Tomaz et al., 2013). Additionally, traditional forest management practices, involving *Quercus* forests, have been employed in the area to maintain dehesas for livestock utilization (Calvo-Palacios, 1977). In La Rioja (Spain), the regional government are at the forefront of the Shrub Clearing Plan (PSC) aimed at creating pastures and decreasing forest fires, which has had a positive impact since its implementation in 1986 (Lasanta et al., 2024). Finally, these strategies vie with the prevalent rewilding approach, where non-intervention allows for a slow transition towards natural forest ecosystems (Conti and Fagarazzi, 2004; Pereira and Navarro, 2015). Our study area, located in the Leza Valley (Iberian System, Spain), shows a historical past marked by intensive livestock and agricultural use. Like many other Mediterranean mountainous regions, it suffered the consequences of rural exodus throughout the 20th century, with the subsequent activation of revegetation processes in marginal areas. Since then, shrubland has been invading these areas, dominating the landscape matrix with up to 41 % of the valley surface covered by 2018 (Cortijos-López et al., 2023). This context provides both a management challenge and an opportunity to promote ecosystem services.

Soil has become more important as a natural resource due to its key role as a carbon sink or source (Johnson and Curtis., 2001; Smith et al., 2008). In the context of global change, the fact that soil can store up to twice more carbon than the atmosphere is not to be overlooked (Lal, 2008; Stockmann et al., 2013). However, soil quality and its capacity to store and mitigate atmospheric carbon can be significantly impacted by LULC changes (Lal, 2004; Sil et al., 2017). An increasing number of studies are evaluating how various LULCs affect soil carbon storage capacity (Chen et al., 2011; Lizaga et al., 2019; Bell et al., 2021). Yet, once we establish this understanding, delving deeper into the dynamics of this process and exploring in more detail becomes imperative. From the proportion of soil organic carbon (SOC) stored in each aggregate size (the smaller the aggregates, the more stable the adsorption of carbon by the soil particles), to the resistance of soil aggregates to different disturbances (as an indicator of their resilience in the environment), and finally, as the main research question, the different density fractions in which SOC is found. In that sense, it is of great interest to know the SOC value for each LULC in the recalcitrant fraction, as it gives us real information on how much carbon is being stored in the long term, and therefore on the suitability of each LULC for climate change adaptation and mitigation.

Aggregate formation is the nucleus of all soil carbon storage mechanisms (Blanco-Canqui and Lal, 2004). Although models of aggregate formation may be varied (Tisdall and Oades, 1982; Oades, 1984; Six et al., 2000), there is a general conception that organic matter contained in macroaggregates is more vulnerable to enzymatic and microbial attacks, while microaggregates (approx. < 2 mm) offer greater protection against disruption. Likewise, soil aggregation physically protects soil organic matter both by spatial separation of microbiota and substrate, and by limiting microbial activity regarding the reduced diffusion of oxygen within the aggregates (Six et al., 2002; Rabot et al., 2018). On the other hand, the stability of soil aggregates, defined by Dexter (1988) as the ability of soil to persist and maintain its structure against the disruptive action of water or other external stressors, is one of the most widely used indicators for studying soil structure (Rabot et al., 2018). This characteristic can be significantly influenced by LULC, soil type and microorganism accessibility to SOC (İlay and Kavdir, 2018; von Haden et al., 2019). In addition, density fractionation is a technique that is becoming more relevant with regard to exploring carbon dynamics and its stabilization mechanisms for the development of long-term storage strategies. In this study, the density fractionation method proposed by Golchin et al. (1994) and modified by Cerli et al. (2012) was used to separate the bulk soil into three types: two non-associated (or weakly associated) organic fractions, with the mineral phase (labile fraction, FLF) and occluded within aggregates (occluded fraction, OLF), and a heavy fraction (HF) where organic matter is strongly bound to the mineral phase.

While exploring the impacts of various management strategies on SOC storage is intriguing, factors such as depth and soil environment type can be equally relevant. Depth has been investigated in some studies, revealing distinct patterns depending on LULC (Hao et al., 2017; Li et al., 2019a). Conversely, the soil environment type (acid or alkaline) has been understudied, although it is proving to exert considerable influence on behaviour patterns under the same management strategy (Yang et al., 2018, 2020) that can be attributed to the pH impact on properties such as cation exchange capacity, microbial activity, or nutrient availability (Cortijos-López et al., 2023, 2024a).

As a consequence, the initial hypothesis of this study establishes that systems that are managed after land abandonment (such as pastures, shrub clearings, or managed forest areas such as dehesas) will exhibit a strong capacity for long-term carbon storage, particularly in alkaline environments. The main objective is to investigate SOC storage across three management strategies for abandoned fields in marginal areas of Mediterranean mountains: secondary succession, forest management via dehesas and afforestation, and shrub clearing and extensive grazing. These SOC dynamics will be examined within two types of soil environments — acid and alkaline — and at different depths (0–40 cm). This main objective entails a series of secondary objectives: i) investigating SOC fractionation and content for each aggregate size; ii) analysing aggregate stability (AS); and iii) evaluating SOC distribution across density fractions to assess their long-term mineralization potential, in all cases based on LULC, soil environment type, and depth.

2. Materials and methods

2.1. Study area

The Leza Valley (Iberian System, Spain) is of interest as it typifies the processes of abandonment and marginalization in mountainous areas within the Mediterranean, while also offering a good example of diverse land management practices.

Covering an area of 274.2 km^2 and ranging in altitude from 600 to 1800 m.a.s.l., the valley shows a Cbf climate classification according to Köppen (AEMET and MTE, 2018). Average temperatures range from 6 °C to 11 °C, with higher and lower altitudes experiencing the extremes. Annual precipitation, ranges from 600 to 1,000 mm, and it is mainly concentrated in spring and autumn, with dry summers, offering the characteristics of a Mediterranean mountain climate (Cuadrat and Vicente-Serrano, 2008).

The Valley boasts gentle relief, with low, eroded slopes, accentuated by fluvial dynamics on the riverbeds. Its lithology gives rise to two primary soil types. Calcic Kastanozems (IUSS Working Group WRB, 2015), predominate in calcareous areas and which are characterized by an organic-rich A horizon and a pH typically ranging between 7 and 8.5. Dystric Cambisols (IUSS Working Group WRB, 2015), dominate areas of quartz sandstones, sandstones, and claystones, with low organic matter content and a pH that varies between 6 and 6.5 (Machín, 1994).

The diverse vegetation covers in the valley reflect the region's history and the managed responses to underlying challenges. Natural forests are predominantly composed of various oak species (*Quercus pyrenaica* in siliceous environments and *Quercus faginea* in calcareous ones) and *Fagus sylvatica*. These are interspersed with pine forests that have been established through afforestation efforts (*Pinus sylvestris* in acid environments and *Pinus nigra* in alkaline ones). In shrublands, which is the most widespread cover due to agricultural abandonment, different species dominate depending on the soil characteristics. In acid environments,

Table 1
Guide of abbreviations for the different LULCs under study.

Strategy	Land use and land cover	Dominant specie and management
Secondary Succession	CRL: cropland	Almond grove under traditional management with shallow tillage and no fertilization (alkaline environments)
	SH: shrubland	With *Cistus laurifolius* (acid environments) and *Genista scorpius* (alkaline environments) as the dominant species, it represents the first stage after abandonment and, therefore, our target LULC on which to implement the management measures
	BS: bushland	Larger species, as *Juniperus communis* (both environments), replaces shrub ones in the second stage after abandonment
	F: forest	It is the climax stage of the natural revegetation process. *Q. pyrenaica* (acid) and *Q. faginea* (alkaline) are the dominant tree species
Forest Management	Af.M: managed afforestation	Afforestation area with *P. sylvestris* (acid) and *P. nigra* (alkaline) of approximately 50–70 years and ~800 trees/ha with thinning and clearing cutting-harvesting practices (trend to ~400 trees/ha), and extensive livestock production
	Af.NM: no managed afforestation	Afforestation area with *P. sylvestris* (acid) and *P. nigra* (alkaline) of approximately 50–70 years and ~800 trees/ha without forestry works or livestock harvesting
	Dh.M: managed dehesa	Silvo-pastoral system of old-cleared forest (~250 years and ~40 trees/ha) characterized by extensive land use, with *Q. pyrenaica* (acid) and *Q. faginea* (alkaline) as the dominant species. Forestry works as thinning (young trees) and clearings, and livestock harvesting are carried out
	Dh.NM: no managed dehesa	Silvo-pastoral system of old-cleared forest (~250 years and ~40 trees/ha) characterized by extensive land use, with *Q. pyrenaica* (acid) and *Q. faginea* (alkaline) as the dominant species. No forestry works or livestock harvesting are carried out
Shrub Clearing and Grazing	YSC: young shrub clearing	Pasture area, with herbaceous dominance (both environments), of less than 5 years since their management through shrub clearing. Stocking rate between 0.5 and 1 LU/ha/year
	MSC: medium shrub clearing	Pasture area, with herbaceous dominance (both environments), of approximately 15 years since their management through shrub clearing. Stocking rate between 0.5 and 1 LU/ha/year
	OSC: old shrub clearing	Pasture area, with herbaceous dominance (both environments), of more than 25 years since their management through shrub clearing. Stocking rate between 0.5 and 1 LU/ha/year
	CP: control pasture	Pasture area that has been grazed for centuries and can be considered as a natural balanced system. Stocking rate between 0.5 and 1 LU/ha/year

***Note*:** All sites were carefully selected to be comparable thanks to personal interviews with stakeholders and the regional government, and GPS information. Management pressures were consistent across same LULCs (regardless of environment) to ensure comparability and minimize inaccuracies.

Cistus laurifolius is the dominant species, while in alkaline environments, the vegetation consists of *Genista scorpius, Thymus vulgaris, Salvia rosmarinus*, and *Buxus sempervirens* (Fernández-Aldana, 2015).

Although secondary succession is the most common process following abandonment (non-management), the study area presents interesting management alternatives. Many Quercus forests have traditionally been utilized for various silvopastoral purposes under the structure of dehesas (Calvo-Palacios, 1977). These areas are characterized by extensive use, alternating forests that have been cleared long ago (approximately 250 years old) with natural pastures. Additionally, conifer afforestation was implemented by national programs during the second half of the 20th century in response to the slow natural revegetation process following abandonment (Ortigosa, 1990). These efforts aimed to regulate hydrological and geomorphological processes associated with soil erosion and flooding (Nadal-Romero et al., 2023a). Notably, shrub clearing and grazing management practices have been implemented. These specific regional measures were initiated in 1986 for socio-economic purposes, aiming to revitalize rural activity. This was done through extensive livestock farming, and due to environmental reasons, focused on fire prevention by removing much of the fire-prone shrubland (Lasanta et al., 2009).

2.2. Soil sampling

Samples were collected from various LULCs for each of the management strategies—secondary succession, forest management, and shrub clearing—within a depth range of 0–40 cm (sampled every 10 cm), and for each soil environment type (Fig. 1). Acid and alkaline environments were previously differentiated based on their bedrock characteristics (derived from geographic information layers) and typical vegetation communities (identified by dominant species of shrubland, pine, or *Quercus* sp.). This allowed the study areas to be classified prior to laboratory pH analysis. pH values oscillated between 4.9 and 7.9, and 6.5 and 8.8 in acid and alkaline environments, respectively. One point in acid sites (medium shrub clearing pasture) presents high pH values, but we have classified these into two groups based on vegetation communities and the complex edaphic processes affecting soil.

Four LULC categories were selected for each management strategy (Table 1). In secondary succession: i) cropland (CRL), almond cultivation representing the initial condition before abandonment (only present for alkaline soils as, at that time, its limited presence did not allow for a control situation to be found in acid environments); ii) shrubland (SH), the initial phase of secondary succession process after abandonment, and the most extended LULC that should be managed; iii) bushland (BS), the subsequent phase where shrubland transitions to larger species; and iv) forest (F), representing the climax state with established tree species. In forest management: i) managed afforestation (Af.M), involving forest operations such as thinning and clear-cutting harvesting, combined with livestock introduction; ii) no managed afforestation (Af.NM); iii) managed dehesa (Dh.M), characterized by extensive livestock farming and shrub clearing; and iv) no managed dehesa (Dh.NM). Lastly, in shrub clearing and grazing: i) young shrub clearing pasture (YSC), cleared less than 5 years ago; ii) medium shrub clearing pasture (MSC), around 15 years since the last intervention; iii) old shrub clearing (OSC), cleared over 25 years ago; and iv) control pasture (CP), areas grazed for so long that they have reached a natural balance. In the case of both secondary succession and shrub clearing, the study adopts a chronosequence approach, where the time factor regarding the progression of both strategies is replaced by spatial analysis (Bonet, 2004), which is based on information provided by land managers and meticulous historical studies of the area. At each point and depth, three composite samples were collected by combining three subsamples, selecting areas with similar altitude, exposure, and topography so as to minimize errors.

2.3. Laboratory analyses

The analyses were conducted in the laboratories of the Pyrenean Institute of Ecology (IPE-CSIC) and the Institute for Biodiversity and Ecosystem Dynamics in the University of Amsterdam (IBED-UvA). Initially, 20 aggregates (approximately 4.5 mm in size) were randomly

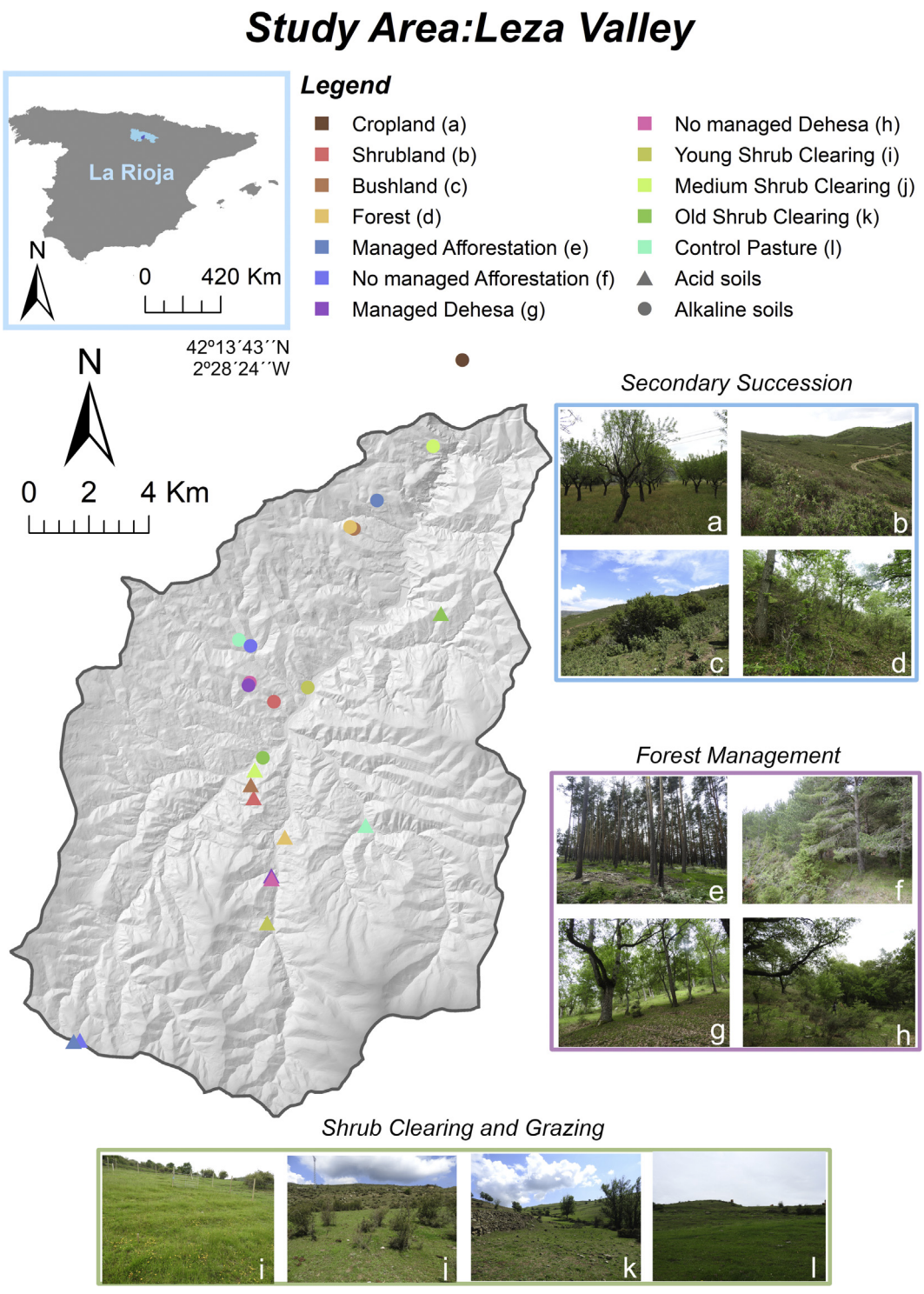


Fig. 1. Study area. Leza Valley in La Rioja (Spain) and location of the different LULCs classified by soil environment type (acid and alkaline). *Note*: lowercase letters on each image denote the LULC type within each management strategy—secondary succession, forest management, and shrub clearing and grazing—as indicated in the legend.

selected from the three soil samples, taken at each point and depth, to analyse their stability using the Drop test (Imeson and Vis, 1984). Water droplets were poured onto each aggregate from a height of 1 m, and the number of drops required to break it, to the extent that its largest fragment passed through a 2 mm mesh, were counted. Subsequent analyses were performed on the fine fraction obtained from air-dried samples and sieved through a 2 mm mesh. The pH was estimated using a pH meter suspended (1:2.5) in deionized water. Texture analysis was conducted using a particle size analyser (Mastersizer 2000, Malvern Panalytical Instruments, Almelo, the Netherlands), following oxidation of organic matter with H_2O_2. Total carbon (C) and total nitrogen (N) were analysed by dry combustion with an oxygen injection using an elemental analyser (Carbon/Nitrogen/Sulphur LECO 928 series LECO CNS 928, St Joseph, MI, USA). SOC content was equivalent to C in acid environments, and the result of subtracting the $CaCO_3$ % (by using the Bernard Calcimeter methodology from which the total

inorganic carbon was calculated) in alkaline environments. SOC values were expressed as both concentration (%) and stock (content per area, Mg ha^{-1}). The SOC/N ratio was estimated from the SOC and N values.

Other sets of sub-samples were air-dried and sieved through 5 mm and 2 mm mesh sizes, dividing them into three size ranges (< 2 mm, 2–5 mm, > 5 mm) for aggregate size fractionation. Subsequently, carbon (C) content was analysed using the elemental analyser, and the soil organic carbon (SOC) content (%) was extracted for each aggregate size (considering $CaCO_3$ in alkaline environments).

Following the methodology of Golchin et al. (1994) and Cerli et al. (2012), density fractionation was carried out on bulk soil samples. Firstly, 10 g of air-dried sample were taken and added, along with 50 ml of sodium polytungstate (NaPT, density of 1.6 g cm^{-3}), into a centrifugation tube. After one hour, the suspension was centrifuged at 6800 × g for 20 min at room temperature. The floating free light fraction (FLF) was separated and collected using a pore glass fiber filter (0.7 μm Whatman GF/F filter), then washed with deionized water until its conductivity reached 200 $\mu S\ cm^{-1}$. The remaining sample was resuspended in NaPT (50 ml) and sonicated (150 J Ml^{-1}) (Sonopuls HD 3200 with a VS70 probe) and calibrated in an ice bath (to maintain the temperature at 40 °C). After the dispersion process, the occluded light fraction (OLF) was extracted by repeating the centrifugation process (6800 × g for 20 min), filtration, and washing with deionized water. To ensure complete sedimentation of the smallest clay-sized particles, the remaining sample was successively washed with deionized water, shacked, and centrifuged until reaching a conductivity of 500 $\mu S\ cm^{-1}$ in the wash water. The resulting soil material yielded the heavy fraction (HF). Finally, the samples were homogenized (HF was milled) and freeze-dried. The different fractions were used for N and SOC content (in the case of HF, the estimated $CaCO_3$ of the HF recovery fraction was considered), and SOC/N ratio determination. The relative contribution of SOC by density fractionation was estimated by multiplying the mass percentage of each fraction by its respective SOC content.

Due to the high number of samples, the time-intensive nature, and the high cost of fractionation analyses, only two samples per LULC, soil environment type and depth (every 10 cm), have been analysed. To address this limitation and enable subsequent statistical analyses, the samples were grouped into two depth categories (0–20 cm and 20–40 cm) for each LULC after analysis. This approach ensured replication at each depth, resulting in four soil samples per LULC for every 20 cm. It is important to consider the limitations arising from this data grouping—stemming from the limited replication in the laboratory analysis and the grouping of the samples at different depths—when interpreting the effects of different management strategies on the results of aggregate size and density fractionation.

2.4. Data and statistical analysis

First, a Factor Analysis of Mixed Data (FAMD) of qualitative and quantitative variable categories was undertaken. Normal distribution was assessed using the Shapiro-Wilk normality test, and variance homogeneity was examined using Levene's test for the different factors. Since normal distribution was not met for many of the study parameters, non-parametric tests—specifically Kruskal-Wallis analyses of variance—were employed to establish differences between LULCs, depth, and soil environment type. Additionally, a post hoc Least Significant Difference (LSD) test was performed to identify differences among LULCs within the same environment and grouped depth. Finally, Spearman's correlation coefficient was used to assess the relationship among the different soil physicochemical properties analyzed, and the correlations were plotted in a correlogram. Statistical significance was considered for analyses with *p*-values below 0.05. The statistical analyses and graphical representations were conducted using IBM SPSS Statistics 25 and RStudio (Version 2022.07.2 Build 576).

3. Results

3.1. Soil organic carbon stock

Cortijos-López et al. (2023, 2024a, 2024b) analysed the differences in physico-chemical soil properties and SOC and N storage (Mg ha^{-1}) in different LULCs, for acid and alkaline environments at different depths. The results of SOC stock in the soil profile (0–40 cm) for each LULC and environment, separated into the three management strategies considered for this article, are shown in Fig. 2. During secondary succession, a progressive SOC increase (not significant) was observed for both environments as succession progressed to the young forest stage (F). Significant differences were observed between CRL and F in alkaline soils, showing an improvement in soil quality and storage regarding time factor. Forest management showed significant differences both between LULC types (dehesas and afforestations) and in the case of afforestations in acid environments. However, no differences were observed between these LULCs in alkaline environments. Af.M from acid environments was found to be the LULC with the highest SOC storage. In shrub clearing management, no significant changes were observed between LULCs in acid environments. In alkaline environments, a significant increase was detected up to approximately 25 years of management (OSC).

Considering SH as the most widespread LULC in the valley (unmanaged after land abandonment), to which the different post-abandonment strategies would be applied, significant higher SOC stocks were found in both afforestation systems in acid environments and Dh.NM in alkaline ones.

3.2. Influence of environment conditions

The influences of different environmental variables in our study were analysed. The results of a FAMD are shown in Fig. 3, where qualitative variables (LULC, soil environment, predominant vegetation species, and intensive use in the past) and quantitative variables (soil depth, altitude, slope, precipitation and temperature) were considered, together accounting for 26 % of the variability. In the plot of qualitative variables, a large contribution in CRL data distribution was observed in Dim 1, and the non-intensive use in the past and the LULCs of dehesas and afforestation in Dim 2. It should be noted how the uses of pasture and secondary succession were grouped together occupying a central position in the plot, while forest management and cultivation created independent groups with a greater contribution to the dispersion of the data.

The graph of quantitative variables showed the predominance of three variables: temperature, precipitation and altitude in the contribution of the data, oriented in opposite directions (temperature inverse to precipitation and altitude) on the axis of Dim 1.

Although the contribution of some environmental variables to the distribution of the data was observed, these only managed to explain 16.9 % and 9.3 % in Dim 1 and Dim 2, respectively. Therefore, this analysis shows that environmental factors are not as relevant in our study, and we continue to focus on the previously established edaphic factors and the detailed analysis of their influence on SOC dynamics.

3.3. Fractionation and SOC content according to aggregate size

SOC content was analysed in three aggregate size ranges (< 2 mm, 2–5 mm, > 5 mm) and the percentage of SOC in each category size with regard to total SOC was obtained (Fig. 4).

SOC was mainly stored in aggregates > 2 mm accounting for more than 53 % of the total SOC content in all LULCs (Fig. 4). The contribution of different aggregate sizes with depth does not show a clear pattern, not even when considering management time (strategies of secondary succession or shrub clearing).

Natural secondary succession and forest management strategies showed higher SOC storages in aggregates < 2 mm in alkaline envi-

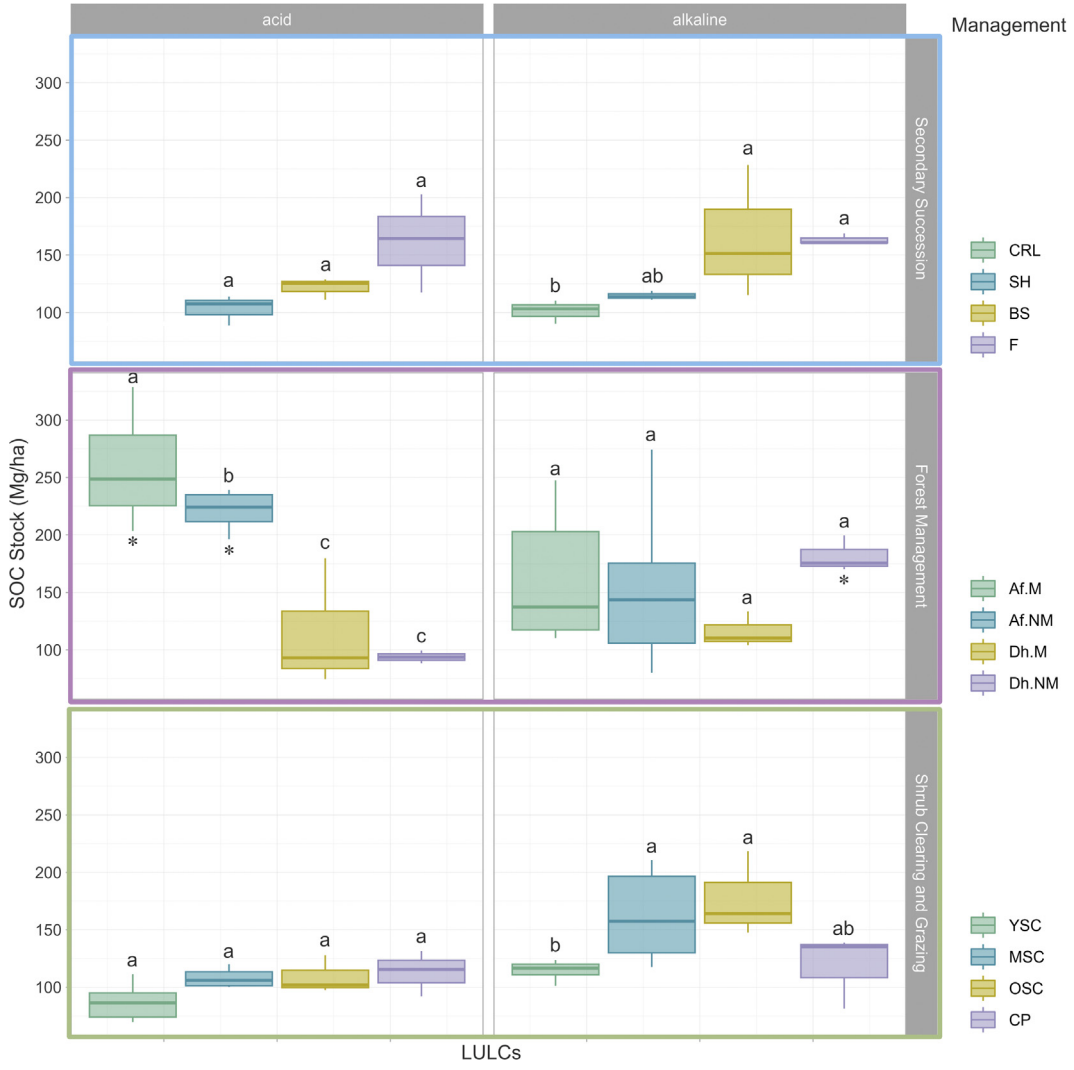


Fig. 2. Soil organic carbon (SOC) stock in the different LULCs and strategies according to soil environment (acid or alkaline) (adapted from Cortijos-López et al., 2023, 2024a, 2024b). Different lower-case letters show significant differences between LULCs within the same strategy and environment. Asterisks show a significant increase in SOC stock within the same environment compared to the target management situation, shrubland. *Note*: CRL, cropland; SH, shrubland; BS, bushland; F, forest; Af.M, managed afforestation; Af.NM, no managed afforestation; Dh.M, managed dehesa; Dh.NM, no managed dehesa; YSC, young shrub clearing; MSC, medium shrub clearing; OSC, old shrub clearing; CP, control pasture.

ronments. In regard to shrub clearing and extensive grazing strategy, this statement was only true during the first years of management; in the old pasture, higher storage in aggregates < 2 mm was observed in acid environments.

Considering SH as reference (current baseline situation in the abandoned marginal areas), pastures management increased the SOC accumulation in aggregates < 2 mm in the long term in acid environments. Higher values were also observed in Dh.NM and BS. In alkaline environments, no LULC exceeded the SOC percentage (< 2 mm) in the topsoil of SH, and only afforestation and YSC exceeded it at 20–40 cm depth.

3.4. Aggregate stability (AS) through water drop impact resistance

AS under water drop impact was examined across all soil depths (Fig. 5 and Fig. S1 in the Supplementary materials). Generally, it was noted that AS was higher in alkaline environments and decreased with depth (with some exceptions such as shrub clearing in acid environments).

When focusing on the topsoil horizon (0–10 cm) (Fig. 5) in acid environments, higher significant AS was observed in afforested sites (as the accumulation line holds a higher proportion of aggregates with a higher number of drops supported), compared to other management controls, such as natural secondary succession (particularly F stage) or shrub clearing in acid environments.

Compared to shrublands, a significant increase in AS was observed in both Af.M and Af.NM, as well as BS, while a slight non-significant improvement occurred with shrub clearing practices. However, a slow secondary succession did not improve AS in the long term (60–100 years).

In alkaline environments (Fig. 5), all the strategies led to the significant enhancement of AS (F, Af.M and Dh.NM and MSC) when compared with shrubland. In general, higher AS was also observed in forest systems (excluding Af.NM).

3.5. Density fractionation and SOC and N distribution among fractions

FLF and OLF fractions only represented a small proportion of the soil mass, while HF fraction recovered a higher proportion (more than 90 % in most cases). Despite soil mass fraction distribution, SOC content in HF only averaged 2 g kg^{-1}. FLF and OLF dataset averages represented a SOC content of approximately 29 g kg^{-1} and 34 g kg^{-1} respectively.

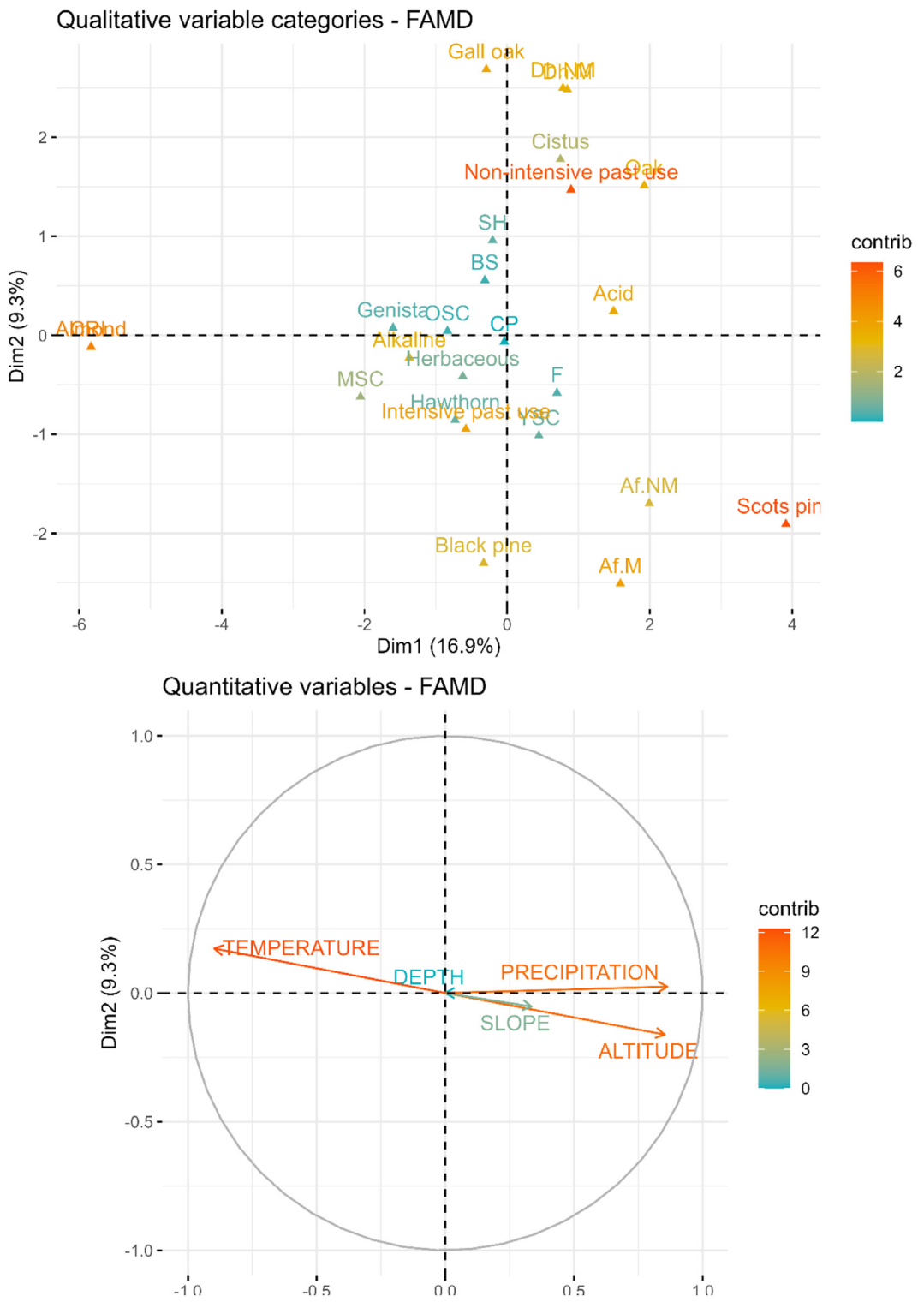


Fig. 3. Factor Analysis of Mixed Data of qualitative variable categories (graph above: LULC, soil environment, predominant vegetation species, and intensive use in the past) and quantitative variables (graph below: soil depth, altitude, slope, precipitation and temperature). *Note*: CRL, cropland; SH, shrubland; BS, bushland; F, forest; Af.M, managed afforestation; Af.NM, no managed afforestation; Dh.M, managed dehesa; Dh.NM, no managed dehesa; YSC, young shrub clearing; MSC, medium shrub clearing; OSC, old shrub clearing; CP, control pasture.

3.5.1. SOC distribution according to soil density fractionation

The distribution of SOC was analysed in terms of its contribution to the total SOC of the samples from each soil fraction across different management strategies and LULCs, both in topsoil (0–20 cm) (Fig. 6) and at depth (20–40 cm) (Fig. S2 in the Supplementary materials). In acid topsoil, the highest and lowest SOC contribution in the FLF were found in BS (28.9 %) and YSC (2.5 %), respectively. To the contrary, an opposite trend was observed in the HF, where the highest value was recorded in YSC (94.5 %). At depth, Af.NM showed the highest SOC contribution in FLF (31.3 %).

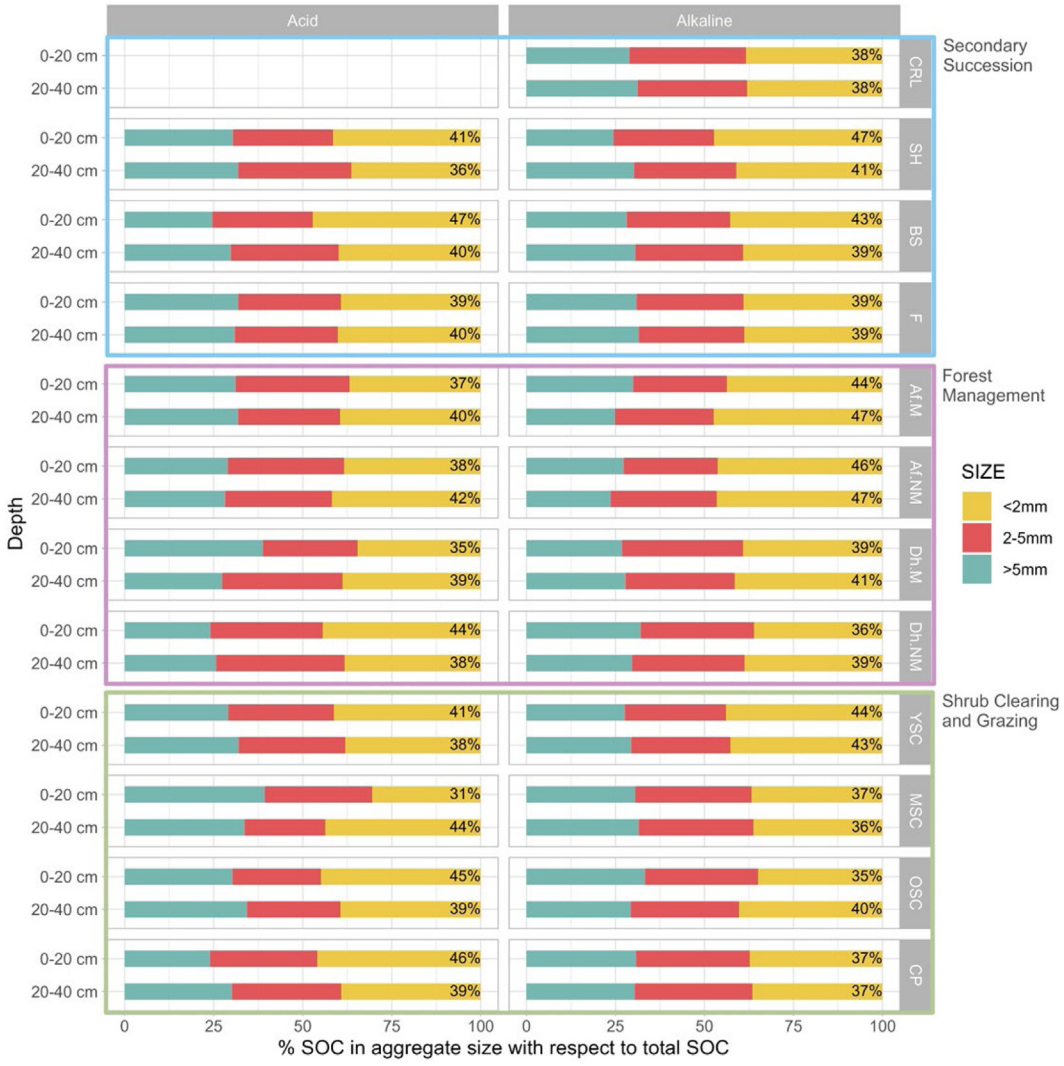


Fig. 4. Soil organic carbon content in three soil aggregate size ranges (< 2 mm; 2–5 mm; > 5 mm) according to two soil environments (acid or alkaline) and three management strategies: secondary succession, forest management, and shrub clearing and grazing. The percentage in the plot indicates the percentage of SOC in < 2 mm aggregates size with respect to total SOC. *Note*: CRL, cropland; SH, shrubland; BS, bushland; F, forest; Af.M, managed afforestation; Af.NM, no managed afforestation; Dh.M, managed dehesa; Dh.NM, no managed dehesa; YSC, young shrub clearing; MSC, medium shrub clearing; OSC, old shrub clearing; CP, control pasture.

On the other hand, the highest HF values were recorded in OSC (96.6 %).

In alkaline environments, across all depths, the highest FLF values were observed in afforested sites (29.3 % in Af.M in the topsoil, and 31.3 % in Af.NM at 20–40 cm), and the highest HF was recorded in OSC (96.2 % and 96.6 % at 0–20 cm and 20–40 cm, respectively).

When focusing on topsoil (Fig. 6), differences between acid and alkaline environments were only evident for the LULCs of forest management.

Observations in acid environments according to management strategy were as follows: i) In secondary succession, no significant differences in carbon mineralization (HF) were observed between the different stages. The significantly higher values of labile SOC in BS coincided with greater AS and SOC proportion in aggregates < 2 mm; ii) In forest management, the higher accumulation of mineral SOC (HF) in dehesas compared to afforested areas, as well as in managed areas compared to unmanaged ones was worth noting. In FLF and OLF, the opposite was observed, with greater contributions in afforested sites. However, no significant differences were observed between any two LULCs within the same fraction; iii) Shrub clearing exhibited an irregular evolution pattern over time in all fractions. The significantly lower value of MSC in HF coincided with the lower proportion of SOC in aggregates < 2 mm and their lesser stability.

In alkaline soil environments, observations varied depending on the type of strategy employed: i) Secondary succession decreased HF contribution with the advancement of revegetation, while increasing labile carbon. However, no significant differences were observed between LULCs. These HF values were also related to the proportion of SOC in aggregates < 2 mm; ii) In forest management, afforested areas exhibited significantly higher FLF values, while dehesas showed higher HF values. Dh.M was identified as the most suitable LULC for long-term carbon storage. No significant differences were observed in OLF among LULCs; and iii) Shrub clearing, similar to the observations in acid soils, did not show a linear increase of SOC in HF over time with management. OSC presented the highest values of SOC in the recalcitrant fraction.

To sum up, the secondary succession strategy did not result in a SOC increase in HF fraction, in neither acid nor alkaline environments, compared to our initial state after abandonment, characterized by shrubland. However, the shrub clearing with extensive grazing displayed a slight increase in recalcitrant carbon in alkaline environments and a sig-

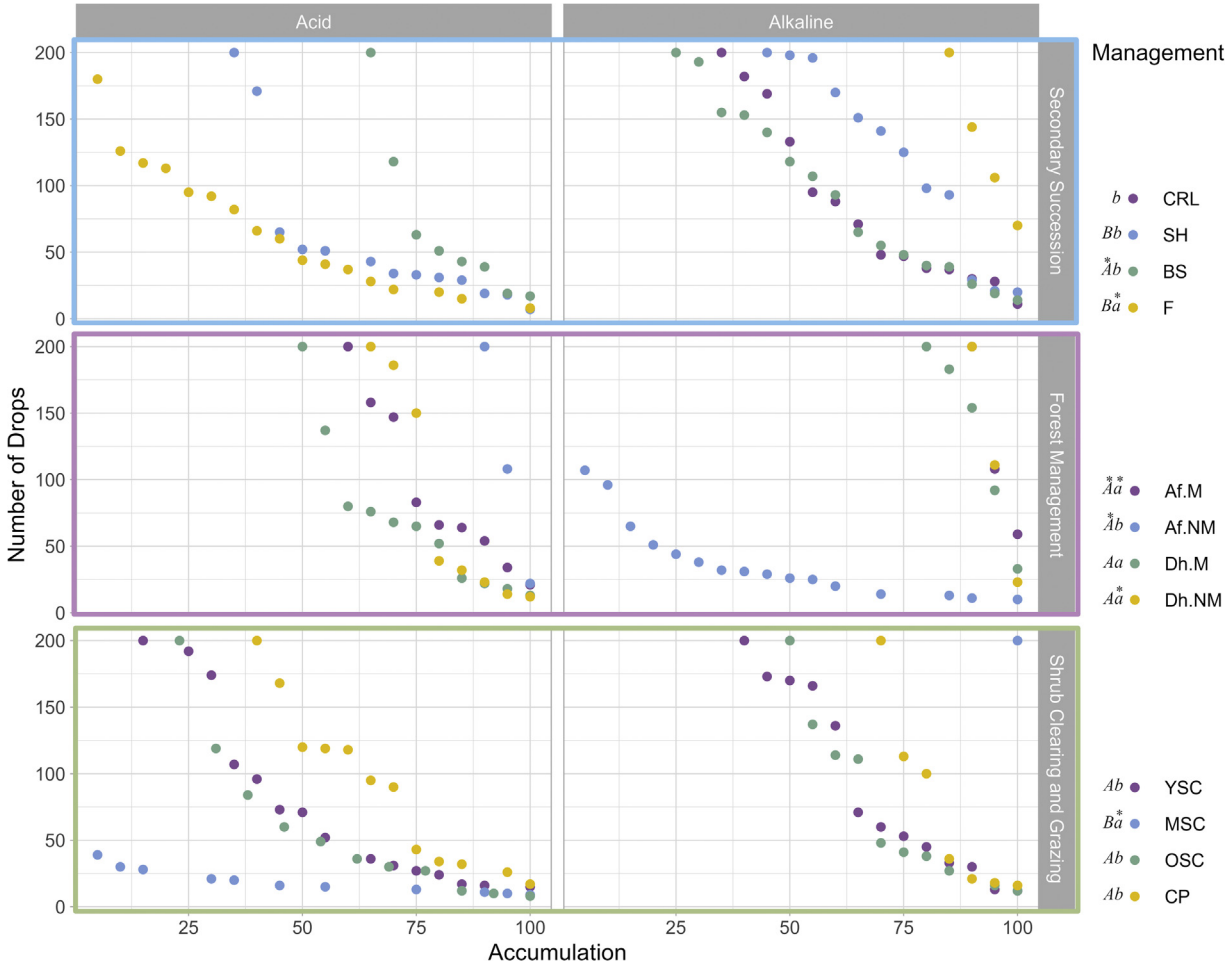


Fig. 5. Aggregate stability (AS) to water drop impact according to LULC, management strategy, and environment (acid or alkaline), for 0–10 cm depth. On the *x*-axis, the cumulative percentage of samples that withstand a certain number of impacts (*y*-axis) without breaking. The letters to the left of the legend: i) in capital letters, different letters show significant differences between LULCs of the same strategy in acid environments; ii) in lower case, different letters show significant differences between LULCs of the same strategy in alkaline environments; iii) asterisks indicate a significant increase in AS when compared to the target management (SH) within the same soil environment (acid or alkaline). *Note*: CRL, cropland; SH, shrubland; BS, bushland; F, forest; Af.M, managed afforestation; Af.NM, no managed afforestation; Dh.M, managed dehesa; Dh.NM, no managed dehesa; YSC, young shrub clearing; MSC, medium shrub clearing; OSC, old shrub clearing; CP, control pasture.

nificant increase in acid ones. Meanwhile, in forest management, only Dh.M stood out in alkaline environments for long-term storage, with afforestations showing prominence in the FLF and OLF fractions.

3.5.2. *SOC/N ratio content according to soil density fractionation*

The distribution of SOC/N ratio for each soil fraction was investigated under different management strategies and LULCs in the topsoil (0–20 cm) (Fig. 7), as well as at depth (20–40 cm) (Fig. S3 in the Supplementary materials). On the topsoil of acid environments, pastures after shrub clearing showed the smallest values in both FLF and HF (12.7 in MSC and 10.0 in OSC, respectively). Af.M exhibited the poorest quality of this parameter across all fractions. At depth, a similar trend was observed except for the highest value of F (17.5) in the HF. In alkaline environments, afforestation once again stood out with the highest values of SOC/N ratio in the labile fraction, both in the topsoil and at depth. However, in the recalcitrant fraction, dehesas stood out in the topsoil (values ranging from 13.1 in Dh.M to 9.8 in Dh.NM), while SH showed the best value at depth (9.8).

Focusing on the topsoil, smaller SOC/N ratios were visibly observed in HF compared to FLF or OLF. Moreover, soils in alkaline environments generally exhibited slightly lower values across most LULCs (Fig. 7).

According to the management strategy, observations taken from acid environments were as follows: i) In secondary succession, the smallest SOC/N ratio was found in F in the HF fraction, while in FLF and OLF, SH showed smaller values. No significant differences were observed between LULCs; ii) The forest management showed the lowest ratios for all fractions in Dh.NM, corresponding to good AS and the highest percentage of SOC in aggregates < 2 mm. Significant differences were observed in the HF fraction between Af.M and Dh.NM. Both afforestation and dehesas appeared to improve this property under unmanaged conditions; and iii) In shrub clearing, no pattern of evolution or change of SOC/N ratio mineralization was observed over time.

In alkaline soil environments, results showed that: i) In secondary succession, forest advancement did not result in an improvement of this property, with the lowest SOC/N ratio observed in SH across all fractions. Significant differences were observed in HF between this initial stage of revegetation and subsequent stages; ii) The forest management once again showed the smallest SOC/N ratio values in the Dh.NM, with significant differences in FLF compared to Af.M and Af.NM, as well as in OLF compared to Af.M; and iii) The shrub clearing exhibited a similar scenario to that of acid environments, where no clear pattern for this parameter could be observed over time, nor was there any increased mineralization (HF fraction).

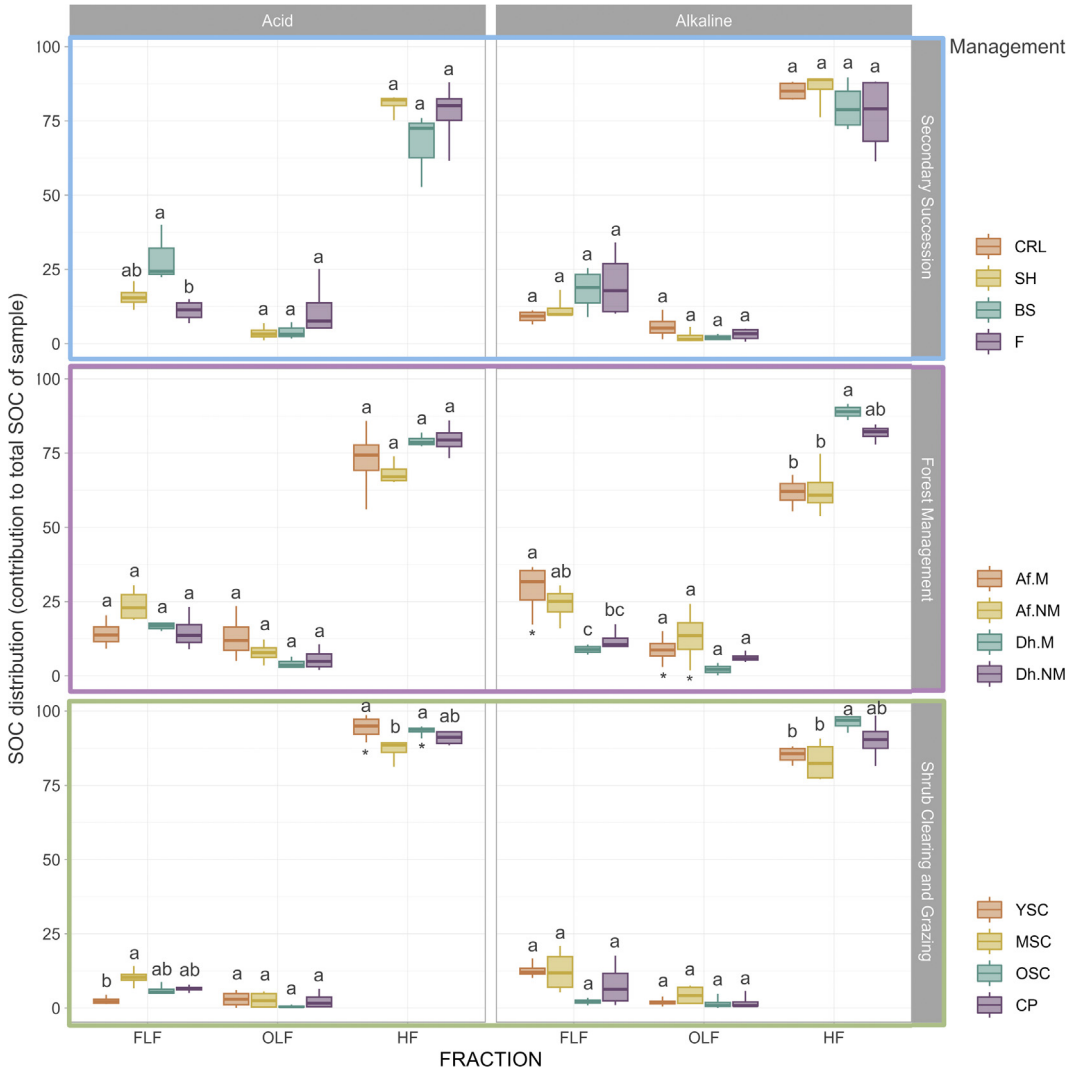


Fig. 6. SOC distribution (contribution to the total sample), in 0–20 cm soil depth, for each soil fraction (FLF: labile fraction; OLF: occluded fraction; HF: mineral fraction), depending on the soil environment (acid or alkaline) and three management strategies: secondary succession; forest management; shrub clearing and grazing. Different lower-case letters show significant differences between LULCs within the same strategy and fraction. Asterisks show a significant increase in SOC content within the same fraction and environment compared to the target management situation, shrubland. *Note*: CRL, cropland; SH, shrubland; BS, bushland; F, forest; Af.M, managed afforestation; Af.NM, no managed afforestation; Dh.M, managed dehesa; Dh.NM, no managed dehesa; YSC, young shrub clearing; MSC, medium shrub clearing; OSC, old shrub clearing; CP, control pasture.

From a global perspective, the most favourable SOC/N values were achieved with the shrub clearing strategy across all three fractions. Furthermore, when considering our baseline condition for the implementation or absence of management (shrubland), a significant diminution in the SOC/N ratio was observed in acid environments, both in FLF (by YSC, MSC, and OSC) and in HF (YSC, OSC, and CP) (Fig. 7).

3.6. Correlation between soil parameters

A higher number of significant correlations between soil properties were found in acid environments than in alkaline ones (Fig. 8).

In acid environments, the value of HF-rec (the percentage contribution of this fraction to the total SOC of the sample) significantly correlated with all soil parameters (except clay content). Moreover, this correlation was only positive with pH value and silt content. It was noteworthy that HF-rec showed a negative correlation with SOC stock in this type of environment. On the other hand, AS demonstrated an inverse response, correlating negatively and significantly with pH and HF-rec, but positively with SOC stock and most of the studied parameters.

In alkaline environments, significant correlations for HF-rec notably decreased. Among them, a positive correlation with clay content stood out. It was worth noting the negative correlation of AS with both pH and carbonate content. It's of particular interest to consider that the strongest positive correlation of mineral SOC (HF C) occurred in both environments with SOC of aggregates between 2 mm and 5 mm.

4. Discussion

4.1. Relevance of environmental factors

Environmental and human factors conditioned SOC evolution after land abandonment. In our location, the influence of environmental factors only accounts for a small portion of data variability (just 26 %). This limited factor may be due to the restricted study area, where variables like temperature, annual precipitation, and altitude—which are present in both literature and our analyses—show little variation between sampling sites (in order to make them comparable). Meanwhile, other factors, such as intensive use in the past, are quite widespread.

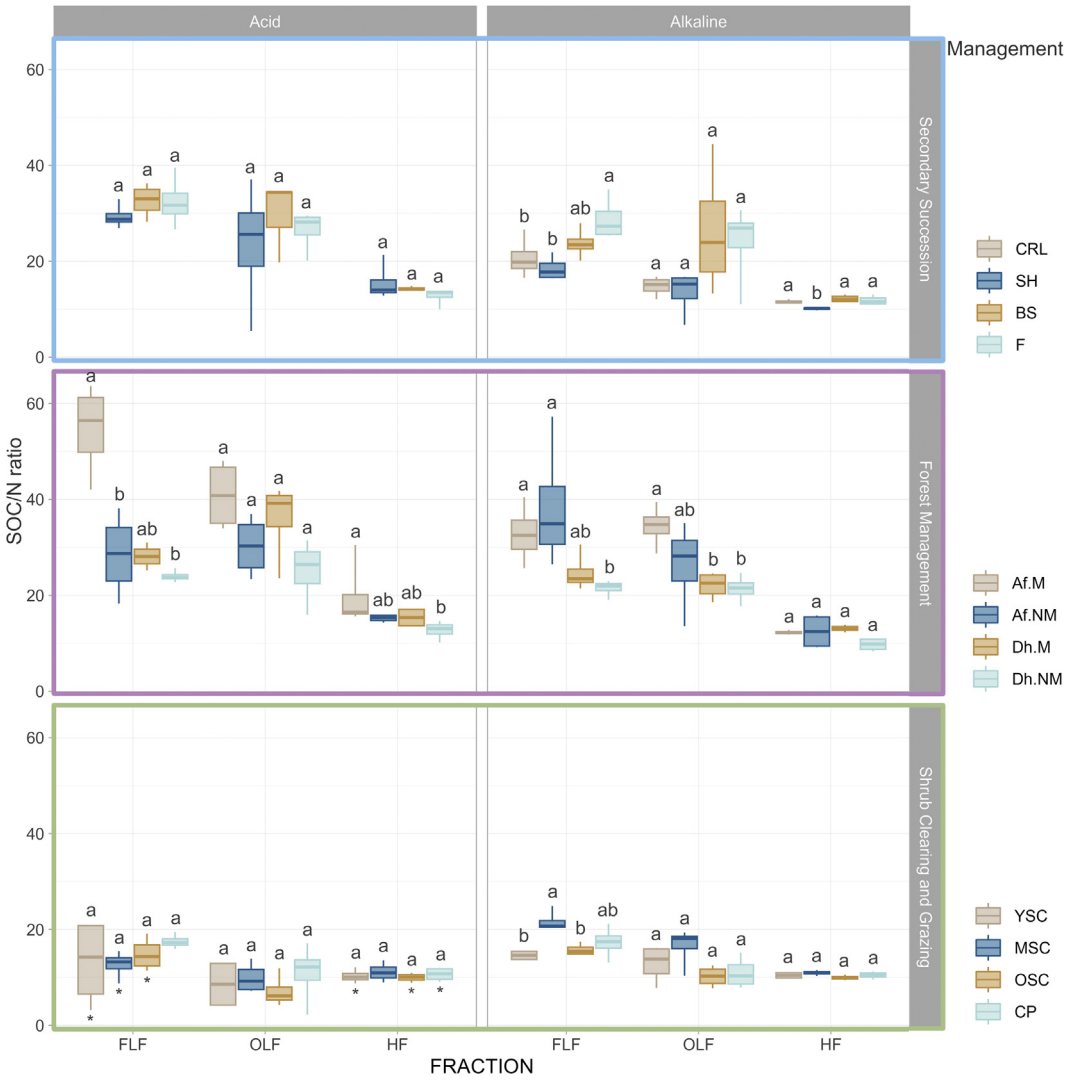


Fig. 7. SOC/N ratio, in 0–20 cm soil depth, for each soil fraction (FLF: labile fraction; OLF: occluded fraction; HF: mineral fraction), according to the soil environment (acid or alkaline) and three management strategies: secondary succession; forest management; shrub clearing and grazing. Different lower-case letters show significant differences between LULCs within the same strategy and fraction. Asterisks show a significant decrease in SOC/N ratio within the same fraction and environment compared to the target management situation, shrubland. *Note*: CRL, cropland; SH, shrubland; BS, bushland; F forest; Af.M, managed afforestation; Af.NM, no managed afforestation; Dh.M, managed dehesa; Dh.NM, no managed dehesa; YSC, young shrub clearing; MSC, medium shrub clearing; OSC, old shrub clearing; CP, control pasture.

In the study area, the landscape was characterised by an intense human impact on the terracing of hillsides for agricultural use and an extensive grazing tradition (Lasanta et al., 2009; Arnáez et al., 2017). Previous studies have noted how continued agricultural use can decrease SOC, regardless of intensification (Haddaway et al., 2017; Crespo et al., 2021). However, Eclesia et al. (2012) found that changes in SOC were independent of initial cover, but highly dependent on current vegetation type, and that precipitation was a factor that could explain up to 50 % of SOC variability. Garcia-Pausas et al. (2007) found that 41 % of SOC variability was explained by altitude, and 57 % by the combination of summer temperatures and precipitation. However, the increase or decrease in SOC, according to climatological variables and altitude, is still controversial and depends on the study area (Martin et al., 2010; Miao et al., 2022).

4.2. SOC content in different aggregate sizes

Soil aggregation and its regulating dynamics can also be affected to a greater or lesser extent by LULC and management, from the breakdown of aggregates by tillage to increased organic matter input by vegetation type (Six et al., 2002; Wright and Hons, 2004).

SOC's association with different aggregate sizes has been previously studied across various LULC. In our study, a generally higher SOC content was observed in aggregates > 2 mm. Usually, a higher proportion of aggregates > 2 mm has been linked to increased SOC content in forests and pastures, regardless of soil environment (Li et al., 2019a; Cheng et al., 2023). However, the stability of aggregates > 2 mm and their consequent SOC content can be influenced by numerous factors. In forest ecosystems, differences have been observed based on species (favourable conditions in broadleaved compared to coniferous forests (Liu et al., 2024)), age (higher content of aggregates > 2 mm and SOC in intermediate stages of restoration (Li et al., 2019a; Bai et al., 2020)), or management practices (greater intensification of forest harvesting resulting in lower soil structural quality (Guo et al., 2021)). These results have been also observed in our study (Fig. 4).

Concerning soil depth, a decrease in SOC content of aggregates < 2 mm was observed with depth, except for forest management systems. Literature shows that both SOC and aggregate > 2 mm content tend to

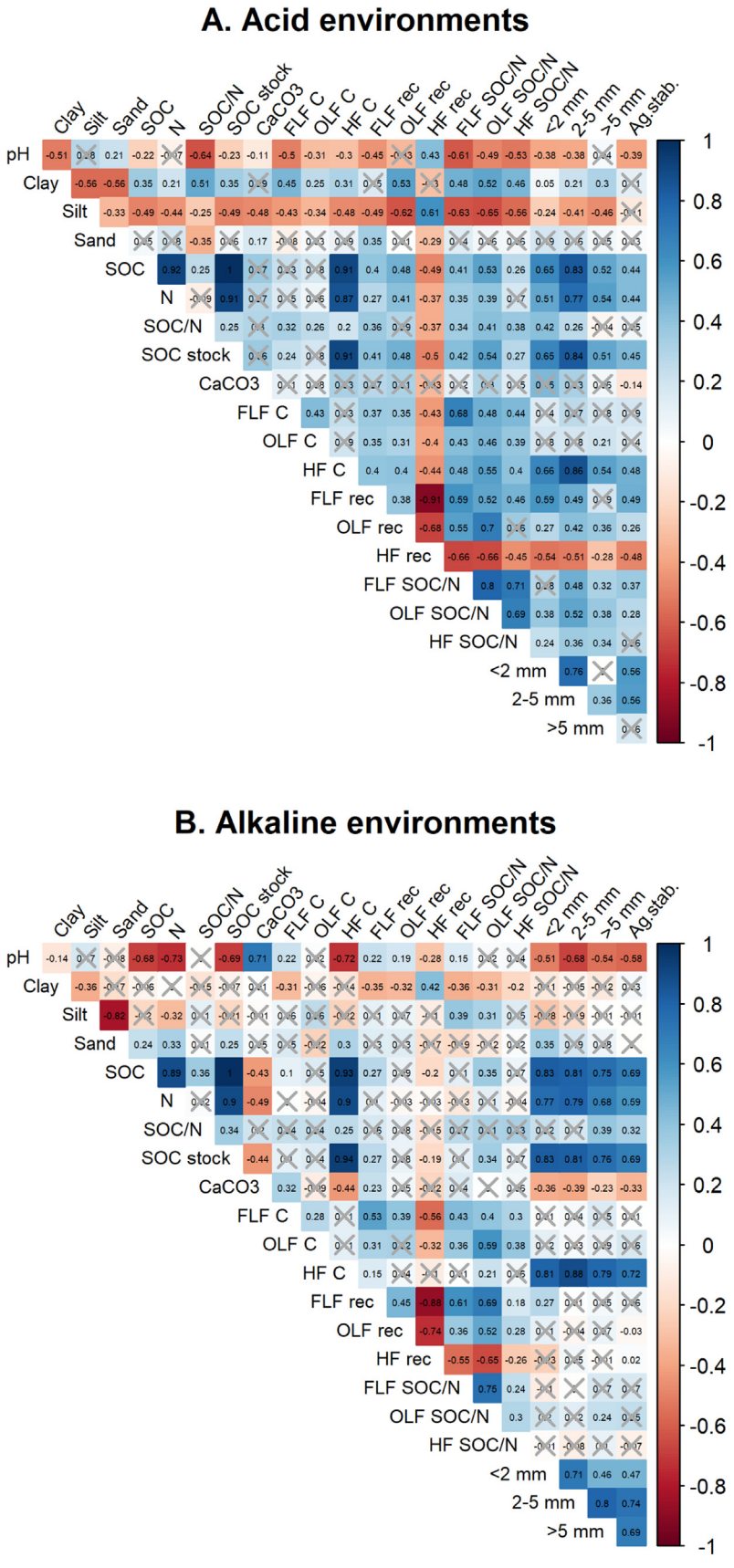


Fig. 8. Correlogram of soil parameters analysed according to the type of environment (acid or alkaline). The degree of negative or positive correlation is shown (red or blue, respectively), and the coefficient of correlation is crossed out when there is not significance (p-value < 0.05). The following parameters are studied: pH, clay, silt, sand, soil organic carbon (SOC), nitrogen content (N), soil organic carbon-nitrogen ratio (SOC/N), soil organic carbon stock (SOC stock), carbonates content ($CaCO_3$), soil organic carbon content in labile fraction (FLF C), soil organic carbon content in occluded fraction (OLF C), soil organic carbon content in mineral fraction (HF C), soil organic carbon contribution to total soil organic carbon of sample in labile fraction (FLF-rec), soil organic carbon contribution to total soil organic carbon of sample in occluded fraction (OLF-rec), soil organic carbon contribution to total soil organic carbon of sample in mineral fraction (HF-rec), soil organic carbon/nitrogen ratio in labile fraction (FLF SOC/N), soil organic carbon/nitrogen ratio in occluded fraction (OLF SOC/N), soil organic carbon/nitrogen ratio in mineral fraction (HF SOC/N), soil organic carbon stock in < 2 mm aggregate size (< 2 mm), soil organic carbon stock in 2–5 mm aggregates size (2–5 mm), soil organic carbon stock in > 5 mm aggregates size (> 5 mm), and aggregate stability (Ag.stab.).

decrease with depth (Bai et al., 2020; Guo et al., 2021). Additionally, studies have noted an increase in SOC concentration in the aggregate < 2 mm fraction with depth in forest systems (Liu et al., 2024).

Regarding soil environment, different patterns were found. In acid environments, an improvement in stable SOC content (aggregates < 2 mm) was achieved when comparing shrublands with the grazing management strategy. However, in alkaline environments, no LULC exceeded stable SOC content of SH in the topsoil. Jiménez et al. (2011) and Grandy and Robertson (2007) observed an increase in SOC within aggregates < 2 mm when transitioning to forest systems in acid environments. However, Liu et al. (2014) did not find any significant increases in SOC aggregates < 2 mm when moving from shrubland to more advanced vegetation states in alkaline ones. This was consistent with our findings (Fig. 4), thus demonstrating the relevance of environmental type in the proportion of different aggregate sizes and their associated SOC content.

4.3. Aggregate stability

Regarding AS, a decrease was observed with depth, while higher levels were noted in alkaline environments compared to acid ones. A decrease with depth has already been observed in previous studies (Cheng et al., 2023; Liu et al., 2024) and may be strongly linked to the reduction in aggregate size (Bai et al., 2020), which in turn is influenced by the spatial distancing of topsoil horizons with greater root presence and organic matter input (Rabot et al., 2018). Regarding soil environment, Han et al. (2016) explained how lower pH can limit the base saturation of the cation exchange capacity, altering reactive minerals such as Al/Fe oxides and influencing aggregate formation and stability. In addition, Bronick and Lal (2005) established that the carbonate content, together with other characteristics such as the proportion of clay or SOC, condition the process of flocculation, cementation and particle regrouping in the formation of stable aggregates.

Focusing on topsoil (Fig. 5), AS in acid soils was significantly improved by afforestation. However, the strategies of shrub clearing (slight increase) and secondary succession (long term decrease), did not result in higher stability. Previous research on acid environments presents varying findings. Some studies, similar to ours, suggest higher stability values in shrubland associated with higher organic matter input from the aboveground biomass (Dorji et al., 2020). In contrast, others studies show stability increases during the transition from cultivation to natural forest or pasture, likely due to enhanced litter input and a possible increase of microbial and fungal biomass (Delelegn et al., 2017). In forest systems, Liu et al. (2024) emphasized the importance of tree species, with higher AS in broadleaved forests than in coniferous ones, justified in easier litter decomposition and higher substance secretion in the soil. Whereas Bai et al. (2020) underscored the management age of forest systems (AS reached its maximum in 20-year-old afforestation) negatively related to plant diversity (mature trees are strong competitors for resources) and consequently impacting on nutrient supply and recycling.

In alkaline environments, both these strategies resulted in the significant improvement of AS compared with post-abandonment situation (Fig. 5). This was also observed by Cheng et al. (2023), with the highest stability values in forests and grasslands. Kalhoro et al. (2017) noted an increase in AS in pastures compared to crops. These authors argue that the enhanced development of the root system together with higher surface litter reserves, increased microbial activity, and organic matter content all promote binding processes that generate more stable aggregates.

4.4. SOC distribution among density fractions

The distribution of SOC across different density fractions was analysed. The process of SOC stabilization is regulated by several mechanisms: i) physical protection through occlusion between aggregates or pores; ii) chemical protection by interaction with organic molecules or mineral surfaces; or iii) selective preservation based on the recalcitrance of certain organic compounds (Marschner et al., 2008). Thus, SOC can be separated into different fractions based on these characteristics, providing information about its composition and persistence capacity in the soil. As observed in our results, the FLF fraction occupies the lowest mass percentage of the soil profile but has high SOC content that still has to undergo microbial and enzymatic digestion, losing much of the carbon in its emission into the atmosphere over the course of these processes. OLF fraction, occluded in the aggregates, provides further SOC protection from disruption. Finally, HF fraction, which occupies the highest percentage of mass, is associated with old, digested SOC, strongly adhered to the mineral surface, but also the least abundant.

It was found that LULCs such as BS (acid environments) and afforestation (both acid and alkaline soils) contributed more to the labile fraction (FLF), while pastures contributed more to the recalcitrant fraction (HF). At this point, it is important to point out, that the greater contribution of labile organic material in afforestations does not convert rapidly into greater carbon accumulation in the mineral fraction (Nadal-Romero et al., 2016; Cortijos-López et al., 2024b). This may be closely linked to the recalcitrant nature of pine needles and the constraints imposed by radiation and temperature on closed forest ecosystems, which in turn hinder microbial decomposition and digestion (Marschner et al., 2008; Li et al., 2019b). On the other hand, grasslands play a prominent role in long-term SOC storage (HF fraction). This observation aligns with findings from other researchers (Nadal-Romero et al., 2023b; Nogueira-Pinheiro et al., 2023) and may be attributed to inputs of residues and nutrients, coupled with increased root biomass, fostering microbial activity and aggregate formation processes (Blanco-Canqui and Lal, 2004; Hao et al., 2017).

Focusing on the topsoil (Fig. 6), only forest management strategy showed differences between environments. In acid soils, secondary succession and shrub clearing did not show a consistent increase in SOC across any fractions over time. Under forest management strategy, differences were observed between dehesas (with higher recalcitrant SOC) and afforestations (more labile SOC), although these differences were not statistically significant.

Previous literature on studies conducted in acid environments shows highly diverse responses. For instance, Mujuru et al. (2013) observed in two soil types (clayey and sandy) that SOC content was higher in natural forests compared to various agricultural management practices, and the mineral fraction was strongly correlated with clay content. However, Guidi et al. (2014) suggested that the transition from managed grassland to old-growth forest increased particulate organic matter but decreased mineral SOC stock, one can assume due to the reduced physical protection of SOC. Pulido-Fernández et al. (2013) also noted that when comparing dehesa areas with shrubland of *Retama sphaerocarpa* no significant differences were observed among LULCs. Li et al. (2019b), on the other hand, examined differences between a reforested watershed and one dominated by shrubland and pasture, finding significantly higher HF values in the latter.

In alkaline environments, the transition to forest systems through secondary succession or afforestation led to an increase in labile SOC and a decrease in recalcitrant SOC (non-significant). Under forest management strategy, dehesas exhibited higher HF content, while in shrub clearing, no relationship between time factor and the SOC content in HF was observed.

When comparing each LULC with the target situation of SH, it was found that in acid environments, only the shrub clearing strategy significantly improved long-term SOC content (HF). In alkaline soils, a slight but non-significant increase in SOC was observed with shrub clearing and dehesas. However, in this environment, afforestation led to a significant increase in organic fractions SOC (FLF and OLF).

The contribution of organic matter according to the type of vegetation or management may increase the proportion of FLF (Six et al., 2002). The fraction of HF may be influenced by physicochemical soil factors (such as clay content), the type of organic matter (more easily degradable compounds), or even practices that may either promote or

hinder microbial activity and thus, the mineralization of organic matter towards more stable phases (Sanderman et al., 2021). Depth also affects the distribution of fractions: in shallower horizons with direct input of organic matter, the labile fraction will predominate, while in deeper horizons, the lack of fresh material input leads to a predominance of HF (Hao et al., 2017; Li et al., 2022). Despite our previous factorial analysis, environmental conditions have proven highly relevant in other studies. For instance, grazing management may be suitable in humid environments, although detrimental in drier ones (Li et al., 2022; Nogueira-Pinheiro et al., 2023). Hence, the importance of field studies prior to regional-scale actions and SOC modelling focused on proper environmental management is underscored.

4.5. SOC/N distribution among density fractions

In both acid and alkaline environment, similar patterns related to SOC/N ratios in density fraction were observed. Overall, pastures exhibited the lowest SOC/N ratio, while afforest areas had the poorest values both at the topsoil and depth across all fractions (Fig. 7 and Fig. S3). When focusing on topsoil (Fig. 7), alkaline soils showed slightly lower SOC/N ratio for most of the LULCs studied.

In acid soils, secondary succession and shrub clearing strategies did not show significant differences in their LULC for any of the fractions. However, in the first case, a positive trend (a decrease in the ratio) over time could be observed in HF. In forest management, Dh.NM, exhibited the lowest ratios, with notable improvement when management was absent. The acid shrubland in our study area, primarily composed of *C. laurifolius*, could be contributing organic matter rich in compounds that are difficult to digest, hindering the use of nutrients in organic fractions (Marschner et al., 2008; Zalegh et al., 2021). This could be further influenced by a low pH and base saturation, potentially limiting microbial activity (Hinsinger et al., 2003; Khandakar et al., 2021). The improvement of SOC/N ratio in HF during the transition to forest was previously observed by Mujuru et al. (2013) in acid soils found in Zimbabwe. Interpreting data in forest management systems becomes more complex, as the tree species and management practices could affect the digestion and recalcitrance of organic matter (Six et al., 2002; Marschner et al., 2008). Previous studies did not find significant differences when comparing dehesas with shrublands (Pulido-Fernández et al., 2013). However, Li et al. (2019b) observed significantly higher N contents in the labile fraction and significantly lower ratios in the mineral fraction in afforested areas compared to pastures and shrubland. They justified it through a probable limited surface microbial activity due to lower soil radiation and temperature in forest systems. Overall, pastures tend to play a significant role in nitrogen input, especially when leguminous species predominate (Hao et al., 2017).

In alkaline soils, secondary succession did not lead to an improvement in this parameter, with the best ratios observed in SH. Forest management and secondary succession strategies showed patterns similar to those in acid environments, with Dh.NM standing out in the former, and an irregular evolutionary pattern in the latter. In this environment, the prevalence of *G. scorpius* in SH was notable which is a leguminous species that also serves as a nurse plant for herbaceous species, shielding them from herbivory and notably increasing nitrogen content (Gómez-Aparicio et al., 2004; Brooker et al., 2008). Throop et al. (2013) also documented this substantial increase in subcanopy shrubland compared to grassland. In forested systems, the higher SOC/N ratio in organic fractions of afforested areas once again stood out. In this context, Nadal-Romero et al. (2023b) observed a significant enhancement of this property during the transition from afforestation or shrubland to pastures.

When considering our post-abandonment baseline (SH), the benefits of shrub clearing management for this property were evident anew (lower values), with its application being significant in acid environments (more demanding).

4.6. Soil properties influencing SOC storage

The correlation analyses revealed a greater number of significant parallels between soil properties in acid environments. Notably, there was a positive correlation between mineral SOC (HF-rec) and pH, and a negative correlation with SOC stock. In contrast, the opposite pattern was observed with AS. These results may indicate that in acid environments (more restrictive), pH behaves as a determining factor in the capacity of the system for long-term SOC storage (system saturation, Bronick and Lal, 2005; Han et al., 2016).

In alkaline environments, a notable positive correlation was observed between recalcitrant SOC (HF-rec) and clay content. The dependency of SOC content on soil properties such as clay type has been emphasized by previous studies (Blanco-Canqui and Lal, 2004; Sanderman et al., 2021). On the other hand, the negative correlation of AS with carbonate content and pH was noteworthy. The former has previously been noted by Throop et al. (2013).

Finally, a strong positive correlation between mineral SOC and 2–5 mm aggregates was found in both environments, consistent with findings from previous studies (Grandy and Roberts, 2007; Li et al., 2019a).

This analysis underscores the importance of distinguishing between acid and alkaline soil environments when devising landscape management plans aimed at enhancing long-term SOC storage.

4.7. Implications for management

Mediterranean mid-mountain regions were extensively exploited from the Middle Ages to the 20th century, resulting in widespread deforestation (García-Ruiz et al., 2020). Since the mid-20th century, socioeconomic marginalization has led to the massive abandonment of agricultural, grazing, and agroforestry activities (Nadal-Romero et al., 2021). LULC changes associated with this abandonment are key factors in shaping the rural landscape in the Mediterranean (Lasanta-Martínez et al., 2005; Sirami et al., 2010). Understanding their implications at different scales is crucial for effective environmental management and the provision of ecosystem services (Padilla et al., 2010; Pelorosso et al., 2011).

This study focuses on SOC storage dynamics as an important tool for climate change mitigation, yielding several key findings: i) Firstly, acid and alkaline soil environments influence the effects of management after land abandonment. ii) The secondary succession strategy has shown better AS and higher SOC content in aggregates < 2 mm during intermediate stages of the revegetation process compared to the climax stage. Although other studies emphasise long-term carbon storage increases with advanced revegetation (Blanco-Canqui and Lal, 2004; Yang et al., 2019), this was not observed in our study area, questioning the effectiveness of the strategy in Mediterranean climates (Nadal-Romero et al., 2016). iii) Forest management has demonstrated improvements in soil AS and increased contributions of organic (labile) material. Thus, this justifies its historical use to mitigate erosion and soil degradation risks (Ortigosa, 1990). Finally, iv) shrub clearing and extensive grazing have improved carbon storage dynamics, with slight increases in SOC content in aggregates < 2 mm and AS, and significant SOC contents in the mineral fraction. This strategy shows promise as a mitigation approach, offering both regulation services (CO_2 mitigation in the atmosphere), and socio-economic benefits (including the revitalization of rural life and its associated activities) (Lasanta et al., 2024).

Creating a mosaic landscape that includes all LULCs, and selecting the most suitable area for each, based on various indicators and previous studies, appears to be the most logical and resilient option for addressing the uncertainties of global change (Lindenmayer et al., 2008; Martínez-Sastre et al., 2017).

5. Conclusions

This study has explored three post land abandonment management strategies—secondary succession, forest management, and shrub clear-

ing and grazing—in two soil environments (acid and alkaline) and at different depths (0–40 cm). The results of this study confirm our initial hypothesis: land management after the abandonment of cultivated fields influences the capacity of soil to store carbon, especially in alkaline environments. In particular, the shrub clearing strategy stands out above other LULCs. This strategy improved AS while also showing a greater contribution of SOC in aggregates < 2 mm and a significant increase in mineral SOC in acid environments. In alkaline soils, AS increased with all strategies, with pastures showing a slight increase in mineral SOC, while afforestation significantly increased labile SOC. The best SOC/ N ratios were consistently observed with the shrub clearing strategy across all soil fractions and environments, accompanied by a higher number of significant correlations in acid soil environments.

In conclusion, in our study area, the shrub clearing strategy stood out, providing long-term carbon storage in the context of global change, while also offering socio-economic benefits for rural development. Nevertheless, we recommend the use of different management practices toward a mosaic landscape approach, where the particular characteristics of each area could be considered — acknowledging the importance of differentiating between environments — allowing for a variety of land uses that contribute different properties and benefits to soil quality.

Declaration of competing interests

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.

CRediT authorship contribution statement

Melani Cortijos-López: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Teodoro Lasanta:** Writing – review & editing, Supervision. **Erik Cammeraat:** Writing – review & editing, Supervision, Resources. **Estela Nadal-Romero:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization.

Acknowledgements

This research project was supported by the MANMOUNT project (PID2019–105983RB-100) funded by the MICINN-FEDER (MICIU/AEI/10.13039/501100011033) and the 570 PRX21/00375 project funded by the Ministry of Universities of Spain from the “Salvador de Madariaga” programme. The ‘Geoenvironmental Processes and Global Change’ (E02_23R) research group is financed by the Aragón Government and the European Social Fund (ESF-FSE). The first author is working with an FPI contract (PRE2020–094509) from the Spanish Ministry of Economy and Competitiveness associated to the MANMOUNT project.

We are thankful for the help of laboratory and fieldwork technicians from the Pyrenean Institute of Ecology (IPE-CSIC) and the Institute of Biodiversity and Ecosystem Dynamics (IBED-UvA) for their assistance during the field and laboratory works.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.geosus.2025.100265.

References

AEMET, MTE, 2018. Agencia Estatal de Meteorología y Ministerio para la Transición Ecológica. Mapas Climáticos de España (1981–2010) y ETo (1996–2016). https://www.aemet.es/documentos/es/conocermas/recursos_en_linea/publicaciones_y_estudios/publicaciones/MapasclimaticosdeEspana19812010/MapasclimaticosdeEspana19812010.pdf.

Arnáez, J., Lana-Renault, N., Ruiz-Flaño, P., Pascual, N., Lasanta, T., 2017. Mass soil movement on terraced landscapes of the Mediterranean mountain areas: a case study of the Iberian Range, Spain. Geogr. Res. Lett. 43 (1), 83–100. doi:10.18172/cig.3211.

Bai, Y., Zhou, Y., He, H., 2020. Effects of rehabilitation through afforestation on soil aggregate stability and aggregate-associated carbon after forest fires in subtropical China. Geoderma 376, 114548. doi:10.1016/j.geoderma.2020.114548.

Bell, S.M., Terrer, C., Barriocanal, C., Jackson, R., Rosell-Melé, A., 2021. Soil organic carbon accumulation rates on Mediterranean abandoned agricultural lands. Sci. Total Environ. 759, 143535. doi:10.1016/j.scitotenv.2020.143535.

Bernués, A., Rodríguez-Ortega, T., Ripoll-Bosch, R., Alfner, F., 2014. Socio-cultural and economic valuation of ecosystem services provided by Mediterranean mountain agroecosystems. PLoS One 9 (7), e102479. doi:10.1371/journal.pone.0102479.

Blanco-Canqui, H., Lal, R., 2004. Mechanisms of carbon sequestration in soil aggregates. Crit. Rev. Plant Sci. 23 (6), 481–504. doi:10.1080/07352680490886842.

Bonet, A., 2004. Secondary succession of semi-arid Mediterranean old fields in south-eastern Spain: insights for conservation and restoration of degraded lands. J. Arid Environ. 56 (2), 213–233. doi:10.1016/S0140-1963(03)00048-X.

Bronick, C.J., Lal, R., 2005. Soil structure and management: a review. Geoderma 124 (1–2), 3–22. doi:10.1016/j.geoderma.2004.03.005.

Brooker, R.W., Maestre, F.T., Callaway, R.M., Lortie, C.L., Cavieres, L.A., Kunstler, G., Liancourt, P., Tielbörger, K., Travis, J.M.J., Anthelme, F., Armas, C., Coll, L., Corcket, E., Delzon, S., Forey, E., Kikvidze, Z., Olofsson, J., Pugnaire, F., Quiroz, C.L., Saccone, P., Schiffers, K., Seifan, M., Touzard, B., Michalet, R., 2008. Facilitation in plant communities: the past, the present, and the future. J. Ecol. 96 (1), 18–34. doi:10.1111/j.1365-2745.2007.01295.x.

Calvo Palacios, J.L., 1977. Los Cameros. De región homogénea a espacio plan. Instituto De Estudios Riojanos, Logroño.

Cerli, C., Celi, L., Kalbitz, K., Guggenberger, G., Kaiser, K., 2012. Separation of light and heavy organic matter fractions in soil—testing for proper density cut-off and dispersion level. Geoderma 170, 403–416. doi:10.1016/j.geoderma.2011.10.009.

Chen, Z., Lue, C., Fan, L., Wu, H., 2011. Effects of land use change on soil organic carbon: a review. Acta Ecol. Sin. 31 (18), 5358–5371.

Cheng, Y., Xu, G., Wang, X., Li, P., Dang, X., Jiang, W., Ma, T., Wang, B., Gu, F., Li, Z., 2023. Contribution of soil aggregate particle size to organic carbon and the effect of land use on its distribution in a typical small watershed on Loess Plateau, China. Ecol. Indic. 155, 110988. doi:10.1016/j.ecolind.2023.110988.

Conti, G., Fagarazzi, L., 2004. Sustainable mountain development and the key-issue of abandonment of marginal rural areas. Planum 11, 1–20.

Cortijos-López, M., Sánchez-Navarrete, P., de la Parra-Muñoz, I., Lasanta, T., Nadal-Romero, E., 2024a. A strategy to enhance soil quality and soil organic carbon stock in abandoned lands: pasture regeneration through shrub clearing. Land Degrad. Dev. 35 (10), 3392–3406. doi:10.1002/ldr.5139.

Cortijos-López, M., Sánchez-Navarrete, P., Lasanta, T., Nadal-Romero, E., 2023. How do acid or alkaline soil environments affect soil organic carbon stocks in a post-abandonment secondary succession process in Mediterranean mountain areas? Catena 232, 107384. doi:10.1016/j.catena.2023.107384.

Cortijos-López, M., Sánchez-Navarrete, P., Lasanta, T., Cammeraat, E.L., Nadal-Romero, E., 2024b. Afforestation, natural secondary forest or Dehesas? Looking for the best post-abandonment forest management for soil organic carbon accumulation in Mediterranean Mountains. Forests 15 (1), 166. doi:10.3390/f15010166.

Crespo, C., Wyngaard, N., Rozas, H.S., Studdert, G., Barraco, M., Gudelj, V., Barbagelata, P., Barbieri, P., 2021. Effect of the intensification of cropping sequences on soil organic carbon and its stratification ratio in contrasting environments. Catena 200, 105145. doi:10.1016/j.catena.2021.105145.

Cuadrat, J.M., Vicente Serrano, S.M., 2008. Características espaciales del clima en La Rioja modelizadas a partir de sistemas de información geográfica y técnicas de regresión espacia. Zubia Monográfico 20, 119–141.

Delelegn, Y.T., Purahong, W., Blazevic, A., Yitaferu, B., Wubet, T., Göransson, H., Godbold, D.L., 2017. Changes in land use alter soil quality and aggregate stability in the highlands of northern Ethiopia. Sci. Rep. 7 (1), 13602. doi:10.1038/s41598-017-14128-y.

Dexter, A.R., 1988. Advances in characterization of soil structure. Soil Tillage Res. 11 (3–4), 199–238. doi:10.1016/0167-1987(88)90002-5.

Dorji, T., Field, D.J., Odeh, I.O., 2020. Soil aggregate stability and aggregate-associated organic carbon under different land use or land cover types. Soil Use Manag. 36 (2), 308–319. doi:10.1111/sum.12549.

Eclesia, R.P., Jobbagy, E.G., Jackson, R.B., Biganzoli, F., Piñeiro, G., 2012. Shifts in soil organic carbon for plantation and pasture establishment in native forests and grasslands of South America. Glob. Change Biol. 18 (10), 3237–3251. doi:10.1111/j.1365-2486.2012.02761.x.

Fernández Aldana, R., 2015. Mapa de los bosques de La Rioja. Gobierno de La Rioja 207 pp. + mapa E. 1:150.000.

Garcia-Pausas, J., Casals, P., Camarero, L., Huguet, C., Sebastia, M.T., Thompson, R., Romanya, J., 2007. Soil organic carbon storage in mountain grasslands of the Pyrenees: effects of climate and topography. Biogeochemistry 82, 279–289. doi:10.1007/s10533-007-9071-9.

García-Ruiz, J.M., Lana-Renault, N., 2011. Hydrological and erosive consequences of farmland abandonment in Europe, with special references to the Mediterranean region – a review. Agric. Ecosyst. Environ. 140 (3–4), 317–338. doi:10.1016/j.agee.2011.01.00.

García-Ruiz, J.M., Tomás-Faci, G., Diarte-Blasco, P., Montes, L., Domingo, R., Sebastián, M., Lasanta, T., González-Sampériz, P., López-Moreno, J.I., Arnáez, J., Beguería, S., 2020. Transhumance and long-term deforestation in the subalpine belt of central Spanish Pyrenees: an interdisciplinary approach. Catena 195, 104744. doi:10.1016/j.catena.2020.104744.

Golchin, A., Oades, J.M., Skjemstad, J.O., Clarke, P., 1994. Study of free and occluded organic matter in soils by 13C CP/MAS NMR spectroscopy and scanning electron microscopy. Aust. J. Soil Res. 32, 285–309. doi:10.1071/SR9940285.

Gómez-Aparicio, L., Zamora, R., Gómez, J.M., Hódar, J.A., Castro, J., Baraza, E., 2004. Applying plant facilitation to forest restoration: a meta-analysis of the use of shrubs as nurse plants. Ecol. Appl. 14 (4), 1128–1138. doi:10.1890/03-5084.

Grandy, A.S., Robertson, G.P., 2007. Land-use intensity effects on soil organic carbon accumulation rates and mechanisms. Ecosystems 10, 59–74. doi:10.1007/s10021-006-9010-y.

Guidi, C., Magid, J., Rodeghiero, M., Gianelle, D., Vesterdal, L., 2014. Effects of forest expansion on mountain grassland: changes within soil organic carbon fractions. Plant Soil 385, 373–387. doi:10.1007/s11104-014-2315-2.

Guo, G., Li, X., Zhu, X., Xu, Y., Dai, Q., Zeng, G., Lin, J., 2021. Effect of forest management operations on aggregate-associated SOC dynamics using a ^{137}Cs tracing method. Forests 12 (7), 859. doi:10.3390/f12070859.

Haddaway, N.R., Hedlund, K., Jackson, L.E., Kätterer, T., Lugato, E., Thomsen, I.K., Jørgensen, H.B., Isberg, P.E., 2017. How does tillage intensity affect soil organic carbon? A systematic review. Environ. Evid. 6 (1), 30. doi:10.1186/s13750-017-0108-9.

Han, L., Sun, K., Jin, J., Xing, B., 2016. Some concepts of soil organic carbon characteristics and mineral interaction from a review of literature. Soil Biol. Biochem. 94, 107–121. doi:10.1016/j.soilbio.2015.11.023.

Hao, X., You, M., Han, X., Li, H., Zou, W., Xing, B., 2017. Redistribution of different organic carbon fractions in the soil profile of a typical chinese mollisol with land-use change. Commun. Soil Sci. Plant Anal. 48 (20), 2369–2380. doi:10.1080/00103624.2017.1358741.

Hinsinger, P., Plassard, C., Tang, C., Jaillard, B., 2003. Origins of rootmediated pH changes in the rhizosphere and their responses to environmental constraints: a review. Plant Soil 248 (1), 43–59. doi:10.1023/A:1022371130939.

İlay, R., Kavdir, Y., 2018. Impact of land cover types on soil aggregate stability and erodibility. Environ. Monit. Assess. 190 (9), 525. doi:10.1007/s10661-018-6847-4.

Imeson, A.C., Vis, M., 1984. Assessing soil aggregate stability by waterdrop impact and ultrasonic dispersion. Geoderma 34 (3–4), 185–200. doi:10.1016/0016-7061(84)90038-7.

IUSS Working Group WRB, 2015.

Jiménez, J.J., Lorenz, K., Lal, R., 2011. Organic carbon and nitrogen in soil particle-size aggregates under dry tropical forests from Guanacaste, Costa Rica—implications for within-site soil organic carbon stabilization. Catena 86 (3), 178–191. doi:10.1016/j.catena.2011.03.011.

Johnson, D.W., Curtis, P.S., 2001. Effects of forest management on soil C and N storage: meta analysis. For. Ecol. Manage. 140 (2–3), 227–238. doi:10.1016/S0378-1127(00)00282-6.

Kalhoro, S.A., Xu, X., Chen, W., Hua, R., Raza, S., Ding, K., 2017. Effects of different land-use systems on soil aggregates: a case study of the Loess Plateau (Northern China). Sustainability 9 (8), 1349. doi:10.3390/su9081349.

Keesstra, S., Nunes, J., Novara, A., Finger, D., Avelar, D., Kalantari, Z., Cerdà, A., 2018. The superior effect of nature based solutions in land management for enhancing ecosystems services. Sci. Total Environ. 610, 997–1009. doi:10.1016/j.scitotenv.2017.08.077.

Khandakar, T., Guppy, C., Rabbi, S.M., Daniel, H., 2021. Poorly crystalline iron and aluminium oxides contribute to the carbon saturation and sorption of dissolved organic carbon in the soil. Soil Use Manag. 37, 120–125. doi:10.1111/sum.12662.

Khorchani, M., Nadal-Romero, E., Lasanta, T., Tague, C., 2021. Effects of vegetation succession and shrub clearing after land abandonment on the hydrological dynamics in the Central Spanish Pyrenees. Catena 204, 105374. doi:10.1016/j.catena.2021.105374.

Lal, R., 2004. Soil carbon sequestration to mitigate climate change. Geoderma 123 (1–2), 1–22. doi:10.1016/j.geoderma.2004.01.032.

Lal, R., 2008. Carbon sequestration. Philos. Trans. R. Soc. B-Biol. Sci. 363 (1492), 815–830. doi:10.1098/rstb.2007.2185.

Lasanta-Martínez, T., Vicente-Serrano, S.M., Cuadrat-Prats, J.M., 2005. Mountain Mediterranean landscape evolution caused by the abandonment of traditional primary activities: a study of the Spanish Central Pyrenees. Appl. Geogr. 25 (1), 47–65. doi:10.1016/j.apgeog.2004.11.001.

Lasanta, T., 2019. Active management against shrubland expansion: seeking a balance between conservation and exploitation in the mountains. Geogr. Res. Lett. 45 (2), 423–440. 10-18172/cig.3726.

Lasanta, T., Arnáez, J., Errea, M.P., Ortigosa, L., Ruiz-Flaño, P., 2009. Mountain pastures, environmental degradation, and landscape remediation: the example of a Mediterranean policy initiative. Appl. Geogr. 29 (3), 308–319. doi:10.1016/j.apgeog.2008.09.006.

Lasanta, T., Cortijos-López, M., Errea, M.P., Llena, M., Sánchez-Navarrete, P., Zabalza, J., Nadal-Romero, E., 2024. Shrub clearing and extensive livestock as a strategy for enhancing ecosystem services in degraded Mediterranean mid-mountain areas. Sci. Total Environ. 906, 167668. doi:10.1016/j.scitotenv.2023.167668.

Li, B.Q., Li, G.L., Fu, Y., Wang, K., 2019a. Distribution of soil organic carbon within aggregate size fractions following the conversion of cropland to black locust forest on the southern Loess Plateau, China. J. Soil Water Conserv. 74 (1), 59–66. doi:10.2489/jswc.74.1.59.

Li, J., Shangguan, Z., Deng, L., 2022. Free particulate organic carbon plays critical roles in carbon accumulations during grassland succession since grazing exclusion. Soil Tillage Res. 220, 105380. doi:10.1016/j.still.2022.105380.

Li, X., Vogeler, I., Schwendenmann, L., 2019b. Soil aggregation and soil fraction associated carbon under different vegetation types in a complex landscape. Soil Res. 57 (3), 215–227. doi:10.1071/SR18193.

Lindenmayer, D., Hobbs, R.J., Montague-Drake, R., Alexandra, J., Bennett, A., Burgman, M., Cale, P., Calhoun, A., Cramer, V., Cullen, P., Driscoll, D., Fahrig, L., Fischer, J., Franklin, J., Haila, Y., Hunter, M., Gibbons, P., Lake, S., Luck, G., MacGregor, C., McIntyre, S., Mac Nally, R., Manning, A., Miller, J., Mooney, H., Noss, R., Possingham, H., Saunders, D., Schmiegelow, F., Scott, M., Simberloff, D., Sisk, T., Tabor, G., Walker, B., Wiens, J., Woinarski, J., Zavaleta, E., 2008. A checklist for ecological management of landscapes for conservation. Ecol. Lett. 11 (1), 78–91. doi:10.1111/j.1461-0248.2007.01114.x.

Liu, M.Y., Chang, Q.R., Qi, Y.B., Liu, J., Chen, T., 2014. Aggregation and soil organic carbon fractions under different land uses on the tableland of the Loess Plateau of China. Catena 115, 19–28. doi:10.1016/j.catena.2013.11.002.

Liu, Y., Sui, X., Hua, H., Liu, X., Chang, Q., Xu, R., Li, M., Mu, L., 2024. Soil aggregate stability and organic carbon content among different forest types in temperate ecosystems in Northeastern China. Forests 15 (2), 279. doi:10.3390/f15020279.

Lizaga, I., Quijano, L., Gaspar, L., Ramos, M.C., Navas, A., 2019. Linking land use changes to variation in soil properties in a Mediterranean mountain agroecosystem. Catena 172, 516–527. doi:10.1016/j.catena.2018.09.019.

Machín, J., 1994. Los suelos. In: García-Ruiz, J.M., Arnáez, J. (Eds.), Geografía De La Rioja, Vol. Tomo 1. Caja de Ahorros de La Rioja, Logroño, pp. 223–249.

Marschner, B., Brodowski, S., Dreves, A., Gleixner, G., Gude, A., Grootes, P.M., Hamer, U., Heim, A., Jandl, G., Ji, R., Kaiser, K., Kalbitz, K., Kramer, C., Leinweber, P., Rethemeyer, J., Schäffer, A., Schmidt, M.W.I., Schwark, L., Wiesenberg, G.L.B., 2008. How relevant is recalcitrance for the stabilization of organic matter in soils? J. Plant Nutr. Soil Sci. 171 (1), 91–110. doi:10.1002/jpln.200700049.

Martin, D., Lal, T., Sachdev, C.B., Sharma, J.P., 2010. Soil organic carbon storage changes with climate change, landform and land use conditions in Garhwal hills of the Indian Himalayan mountains. Agric. Ecosyst. Environ. 138 (1–2), 64–73. doi:10.1016/j.agee.2010.04.001.

Martínez-Sastre, R., Ravera, F., González, J.A., Santiago, C.L., Bidegain, I., Munda, G., 2017. Mediterranean landscapes under change: combining social multicriteria evaluation and the ecosystem services framework for land use planning. Land Use Policy 67, 472–486. doi:10.1016/j.landusepol.2017.06.001.

Miao, J., Xie, T., Han, S., Zhang, H., He, X., Ren, W., Song, M., He, L., 2022. Characteristics of soil organic carbon in croplands and affecting factors in Hubei Province. Agronomy 12 (12), 3025. doi:10.3390/agronomy12123025.

Mujuru, L., Mureva, A., Velthorst, E.J., Hoosbeek, M.R., 2013. Land use and management effects on soil organic matter fractions in Rhodic Ferralsols and Haplic Arenosols in Bindura and Shamva districts of Zimbabwe. Geoderma 209, 262–272. doi:10.1016/j.geoderma.2013.06.025.

Nadal-Romero, E., Cammeraat, E., Pérez-Cardiel, E., Lasanta, T., 2016. How do soil organic carbon stocks change after cropland abandonment in Mediterranean humid mountain areas? Sci. Total Environ. 566, 741–752. doi:10.1016/j.scitotenv.2016.05.031.

Nadal-Romero, E., Llena, M., Cortijos-López, M., Lasanta, T., 2023a. Afforestation after land abandonment as a nature-based solution in Mediterranean mid-mountain areas: implications and research gaps. Curr. Opin. Environ. Sci. Health 34, 100481. doi:10.1016/j.coesh.2023.100481.

Nadal-Romero, E., Khorchani, M., Gaspar, L., Arnáez, J., Cammeraat, E., Navas, A., Lasanta, T., 2023b. How do land use and land cover changes after farmland abandonment affect soil properties and soil nutrients in Mediterranean mountain agroecosystems? Catena 226, 107062. doi:10.1016/j.catena.2023.107062.

Nadal-Romero, E., Rubio, P., Kremyda, V., Absalah, S., Cammeraat, E., Jansen, B., Lasanta, T., 2021. Effects of agricultural land abandonment on soil organic carbon stocks and composition of soil organic matter in the Central Spanish Pyrenees. Catena 205, 105441. doi:10.1016/j.catena.2021.105441.

Nogueira-Pinheiro, E., Costa-Campos, M.C., Gomes de Brito-Filho, E., da Cunha, J.M., Ferreira-Leite de Lima, A., Silva-Martins, T., de Oliveira-Dias, B., Freire-da Silva, R., Gomes-de Almeida, R., Vinício-dos Santos, R., 2023. Fracionamento físico do carbono e suas interações com os atributos do solo em áreas de pastagens cultivadas e floresta na Amazônia Ocidental. Revista Brasileira de Geografía Física 16 (6), 2978–2993. https://periodicos.ufpe.br/revistas/rbgfe.

Oades, J.M., 1984. Soil organic matter and structural stability, mechanisms and implications for management. Plant Soil 76, 319–337. doi:10.1007/978-94-009-6101-2_28.

Ortigosa, L.M., García-Ruiz, J.M., Gil, E., 1990. Land reclamation by reforestation in the Central Pyrenees. Mt. Res. Dev. 10 (3), 281–288. doi:10.2307/3673607.

Padilla, F.M., Vidal, B., Sánchez, J., Pugnaire, F.I., 2010. Land-use changes and carbon sequestration through the twentieth century in a Mediterranean mountain ecosystem: implications for land management. J. Environ. Manage. 91 (12), 2688–2695. doi:10.1016/j.jenvman.2010.07.031.

Pelorosso, R., Della Chiesa, S., Tappeiner, U., Leone, A., Rocchini, D., 2011. Stability analysis for defining management strategies in abandoned mountain landscapes of the Mediterranean basin. Landsc. Urban Plan. 103 (3–4), 335–346. doi:10.1016/j.landurbplan.2011.08.007.

Pereira, H.M., Navarro, L.M., 2015. Rewilding European Landscapes. Springer International Publishing, Heidelberg doi:10.1007/978-3-319-12039-3.

Pueyo, Y., Beguería, S., 2007. Modelling the rate of secondary succession after farmland abandonment in a Mediterranean mountain area. Landsc. Urban Plan. 83, 245–254. doi:10.1659/0276-4741(2003)023, [0362:LUALCC]2.0.CO;2.

Pulido-Fernández, M., Schnabel, S., Lavado-Contador, J.F., Mellado, I.M., Pérez, R.O., 2013. Soil organic matter of Iberian open woodland rangelands as influenced by vegetation cover and land management. Catena 109, 13–24. doi:10.1016/j.catena.2013.05.002.

Rabot, E., Wiesmeier, M., Schlüter, S., Vogel, H.J., 2018. Soil structure as an indicator of soil functions: a review. Geoderma 314, 122–137. doi:10.1016/j.geoderma.2017.11.009.

Sanderman, J., Baldock, J.A., Dangal, S.R., Ludwig, S., Potter, S., Rivard, C., Savage, K., 2021. Soil organic carbon fractions in the Great Plains of the United States: an application of mid-infrared spectroscopy. Biogeochemistry 156 (1), 97–114. doi:10.1007/s10533-021-00755-1.

Sil, Â., Fonseca, F., Gonçalves, J., Honrado, J., Marta-Pedroso, C., Alonso, J., Ramos, M., Azevedo, J.C., 2017. Analysing carbon sequestration and storage dynamics in a changing mountain landscape in Portugal: insights for management and planning. Int. J. Biodivers. Sci. Ecosyst. Serv. Manage. 13 (2), 82–104. doi:10.1080/21513732.2017.1297331.

Sirami, C., Nespoulous, A., Cheylan, J.P., Marty, P., Hvenegaard, G.T., Geniez, P., Schatz, B., Martin, J.L., 2010. Long-term anthropogenic and ecological dynamics of a Mediterranean landscape: impacts on multiple taxa. Landsc. Urban Plan 96 (4), 214–223. doi:10.1016/j.landurbplan.2010.03.007.

Six, J., Conant, R.T., Paul, E.A., Paustian, K., 2002. Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. Plant Soil 241, 155–176. doi:10.1023/A:1016125726789.

Six, J., Paustian, K., Elliott, E.T., Combrink, C., 2000. Soil structure and organic matter. I. Distribution of aggregate-size classes and aggregate associated carbon. Soil Sci. Soc. Am. J. 64, 681–689. doi:10.2136/sssaj2000.642681x.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M., Smith, J., 2008. Greenhouse gas mitigation in agriculture. Philos. Trans. R. Soc. B-Biol. Sci. 363 (1492), 789–813. doi:10.1098/rstb.2007.2184.

Stockmann, U., Adams, M.A., Crawford, J.W., Field, D.J., Henakaarchchi, N., Jenkins, M., Minasny, B., McBratney, A.B., Courcelles, V.D.R.D., Singh, K., Wheeler, I., Abbott, L., Angers, D.A., Baldock, J., Bird, M., Brookes, P.C., Chenu, C., Jastrow, J.D., Lal, R., Lehmann, J., O'Donnell, A.G., Parton, W.J., Whitehead, D., Zimmermann, M., 2013. The knowns, known unknowns and unknowns of sequestration of soil organic carbon. Agric. Ecosyst. Environ. 164, 80–99. doi:10.1016/j.agee.2012.10.001.

Throop, H.L., Lajtha, K., Kramer, M., 2013. Density fractionation and ^{13}C reveal changes in soil carbon following woody encroachment in a desert ecosystem. Biogeochemistry 112, 409–422. doi:10.1007/s10533-012-9735-y.

Tisdall, J.M., Oades, J.M., 1982. Organic matter and water stable aggregates in soils. J. Soil Sci. 33, 141–163. doi:10.1111/j.1365-2389.1982.tb01755.x.

Tomaz, C., Alegria, C., Monteiro, J.M., Teixeira, M.C., 2013. Land cover change and afforestation of marginal and abandoned agricultural land: a 10 year analysis in a Mediterranean region. For. Ecol. Manage. 308, 40–49. doi:10.1016/j.foreco.2013.07.044.

von Haden, A.C., Kucharik, C.J., Jackson, R.D., Marín-Spiotta, E., 2019. Litter quantity, litter chemistry, and soil texture control changes in soil organic carbon fractions under bioenergy cropping systems of the North Central U.S. Biogeochemistry 143 (3), 313–326. doi:10.1007/s10533-019-00564-7.

Wright, A.L., Hons, F.M., 2004. Soil aggregation and carbon and nitrogen storage under soybean cropping sequences. Soil Sci. Soc. Am. J. 68 (2), 507–513. doi:10.2136/sssaj2004.5070.

Yang, B., Zhang, W., Lu, Y., Zhang, W., Wang, Y., 2019. Carbon storage dynamics of secondary forest succession in the central Loess Plateau of China. Forests 10 (4), 342. doi:10.3390/f10040342.

Yang, S., Cammeraat, E., Jansen, B., den Haan, M., van Loon, E., Recharte, J., 2018. Soil organic carbon stocks controlled by lithology and soil depth in a Peruvian alpine grassland of the Andes. Catena 171, 11–21. doi:10.1016/j.catena.2018.06.038.

Yang, S., Jansen, B., Kalbitz, K., Chunga Castro, F.O., van Hall, R.L., Cammeraat, E.L.H., 2020. Lithology controlled soil organic carbon stabilization in an alpine grassland of the Peruvian Andes. Environ. Earth Sci. 79 (2), 66. doi:10.1007/s12665-019-8796-9.

Zalegh, I., Akssira, M., Bourhia, M., Mellouki, F., Rhallabi, N., Salamatullah, A.M., Alkaltham, M.S., Khalil Alyahya, H., Mhand, R.A., 2021. A review on *Cistus* sp.: phytochemical and antimicrobial activities. Plants 10 (6), 1214. doi:10.3390/plants10061214.