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Shrub clearing and extensive livestock as a strategy for enhancing ecosystem services in degraded Mediterranean mid-mountain areas

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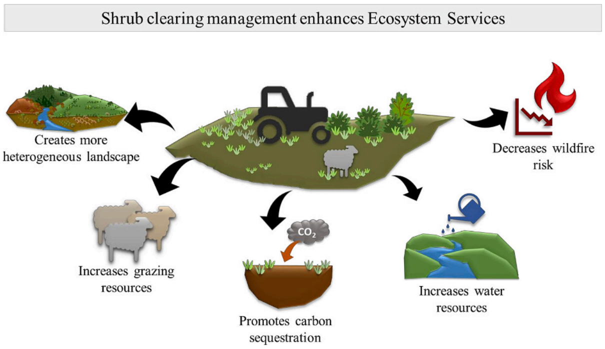
HIGHLIGHTS

- Land abandonment in the Mediterranean mountains has led to a lack of ecosystem services (ES).
- We analyse the effects on ecosystem services of pairing shrub clearing with grazing in an experimental area.
- Landscape diversity, pasture, fire control, soil organic carbon and water resources have been evaluated.
- Managing the Mediterranean mid-mountains could be a very effective strategy to improve the supply of ES.
- Shrub clearing plan also contributes to local development by increasing livestock numbers.

GRAPHICAL ABSTRACT



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ABSTRACT

Land abandonment in the Mediterranean mountains since the 20th century has led to a reduction of ecosystem services, due to revegetation and homogenization of the landscape. To counteract these effects, the regional administration of La Rioja in Spain initiated a Plan for Shrub Clearing (PSC) combined with extensive livestock grazing in 1986, which is still in action today. This study analyses the effects of pairing clearing with grazing in an experimental area of the Leza valley (Iberian System) on: (i) the landscape structure and structural diversity; (ii) the production of pasture; (iii) fire control; (iv) soil organic carbon sequestration (also considering soil environmental types); (v) surface water resources. The results show that: (i) a more fragmented landscape with greater diversity is created; (ii) grazing land is almost doubled in alkaline soils and four-fold in siliceous soils; (iii) fires are considerably reduced, with the mean surface fire spread falling from 34.1 ha/year from 1968 to 1985, to 1.2 ha/year between 1986 and 2022; (iv) regenerated post-clearance grazing soils sequester more organic carbon than that of shrublands, especially older clearings on alkaline soils (55.3 % more); (v) clearing increases hydrological connectivity and water resources. The conclusion is that managing the Mediterranean mid-mountains could be a very effective strategy to improve the supply of certain ecosystem services and improve the current socio-economic perspective of these marginal areas in a context of Global Change. The PSC also contributes to local development by increasing livestock numbers.

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1. Introduction

Restoring degraded landscapes is a good strategy for recovering services (assets and resources) that ecosystems provide to humans (Galati et al., 2016; Keesstra et al., 2018). Land management can also bring economic, landscape and environmental advantages on a local scale by contributing to sustainable development (Quetier et al., 2005; Kleijn et al., 2006; Lasanta et al., 2015). Many landscapes and ecosystems undergo significant abandonment and degradation due to socio-economic changes, poor management or induced alterations in the natural water, carbon or nitrogen cycle (Keenleyside and Tucker, 2010; García-Ruiz and Lana-Renault, 2011; Arnáez et al., 2015; Tarrasón et al., 2016). Public policies from the EU and organisations such as the UN have recently attempted to rehabilitate and restore degraded landscapes, by financing activities to help settle the population in the area, boost sustainable development and maintain biodiversity (MacDonald et al., 2000; Laguna Marín-Yaseli and Lasanta-Martínez, 2007; IEEP and Alterra, 2010; Griggs et al., 2013).

The Mediterranean mid-mountains in Europe are heavily degraded, due to: (i) intensive use since the Late Middle Ages at least, in a context of almost complete self-sufficiency, and (ii) abandonment in the last century without any conservation measures. Intensive use in the past led to deforestation, often by fire, of most of the terrain to create agricultural fields and grazing land (Puigdefábregas and Fillat, 1986; Bal et al., 2011; Cunill et al., 2012; Olarieta et al., 2008), but severely impacting soil erosion, landscape degradation and the loss of natural resources (Arnáez et al., 2011; Nadal-Romero et al., 2013; Lasanta et al., 2017). However, throughout the last century the opposite occurred, with socio-economic marginalisation of the area (Arnáez et al., 2015; Lasanta et al., 2017). Marginalisation included emigration of the population, abandonment of agricultural fields and grazing land, and the underutilisation of forestry products (García-Ruiz and Lasanta-Martínez, 1990; Collantes, 2004; Casasús et al., 2007). As a result, there is mass revegetation on the slopes with shrubland and forest succession, also densification of the existing forests (Molinillo et al., 1997; Poyatos et al., 2003; Roura-Pascual et al., 2005; Pueyo and Beguería, 2007; Komac et al., 2013). On the other hand, some areas used intensively in the past underwent heavy erosion, as is happening on many terraced slopes, from the lack of maintenance work to prevent soil water saturation (Gallart et al., 1994; Lasanta et al., 2001; Arnáez et al., 2015; Brandolini et al., 2018).

Revegetation is certainly the most important post-abandonment process, which has some positive aspects, including: edaphic (i.e., increased aggregate stability, improved fertility, more soil organic matter and carbon over the long-term, lower erosion rates), hydrological (i.e., fewer and smaller floods and better regulation of the hydrological cycle), and a more natural landscape with greater biodiversity in the early stages of plant succession (Keesstra et al., 2018; Lasanta, 2019). However, in the Mediterranean mid-mountains, plant succession is very slow, and for many decades (or even more than a century on very degraded slopes; see i.e. Lasanta et al., 2017) was dominated by succession shrubland, the core element of the landscape (García-Ruiz and Lana-Renault, 2011; Peña-Angulo et al., 2019). Massive shrubland cover on the slopes has negative effects on a local scale and on ecosystem services (ES) that can be transferred to adjoining areas (Gibon, 2005; Hazeu et al., 2010; Bernués et al., 2014), since it reduces the river flow and water supply to the nearby lowland areas (López-Moreno et al., 2011); it increases the fire risk (Pausas and Keeley, 2009; Sil et al., 2019); it reduces landscape diversity (Sitzia et al., 2010), aesthetic quality (Benjamin et al., 2007), and biodiversity in cultural landscapes (Kleijn et al., 2006); it makes a decisive contribution to the loss and degradation of grazing land (Gartzia et al., 2014), and endangers sustainability in the region (Conti and Fagarazzi, 2004). Therefore, revegetation in mountain areas is considered to be one of the changes in land use with the greatest environmental and socio-economic impact (García-Ruiz and Lana-Renault, 2011; San Román-Sanz et al., 2013).

The Mediterranean mid-mountains have few options for integrating into the current economic situation, as they cannot specialise in high-demand products and develop intensive production systems. It must be remembered that they have all the disadvantages of mountain areas: few flat spaces, very steep slopes, climate restrictions, low population, lack of services, poor infrastructures and a highly degraded landscape from over-use in the past. In addition, it does not have the advantages of the alpine mountains: abundant grazing and forest resources, more opportunities for tourism and infrastructure, and towns with sufficient people to maintain services and revitalise the economy (Puigdefábregas and Fillat, 1986; García-Ruiz and Lasanta-Martínez, 1990; Navarro and Pereira, 2012; Sancho-Reinoso, 2013). Thus, they are now classed as poverty traps, due to the scant resources, low returns on investment, and lack of social services and opportunities for development (Conti and Fagarazzi, 2004; Ruben and Pender, 2004). Incorporating it into the general economic system is only possible through activities that do not demand many workers (extensive livestock farming, reforestation, hunting, obtaining by-products from the hillsides, etc.), with few production costs and very low productivity (Bernués Jal, 2007; Marey-Pérez and Rodríguez-Vicente, 2009; Olaizola et al., 2015).

In this context, extensive livestock farming is a highly effective tool for socio-economic revitalisation of the Mediterranean mid-mountains, while at the same time benefiting the environment and landscape (Gellrich et al., 2007; Stoate et al., 2009; Ruiz-Mirazo and Robles, 2012; Rodríguez-Ortega et al., 2014; Nadal-Romero et al., 2018a). In addition, it maintains pastures and extensive grazing, which are beneficial to the climate and environment and included in the Common Agricultural Policy (CAP) (PEPAC, 2023). However, even extensive livestock farming meets difficulties due to the lack of pasture due to shrub revegetation in the last few decades (Molinillo et al., 1997; Bartolomé et al., 2005; Gartzia et al., 2016). Wide areas in the Mediterranean mountains could be grazed if the shrubs preventing livestock from accessing the herbaceous layer beneath the shrub land were eliminated (Lasanta et al., 2006). Land managers and livestock farmers clear or burn shrubs to help extensive farming and provide rural areas with employment (Ruiz-Mirazo et al., 2011; San Emeterio et al., 2016).

Shrub clearing in selected areas (especially accessible abandoned fields with moderate slopes and sufficiently fertile to produce pasture) has been a normal practice for over three decades in some sectors of the Mediterranean mid-mountains in Spain (Valdelvira and Balcells, 1986; Lasanta et al., 2009a). However, little is known about its effects on some ES, especially on supply (production of pasture and water) and regulation (water cycle, soil fertility, climate regulation) in which the Mediterranean mountains could play an important role. This article summarizes the main implications of the pairing shrub clearing - extensive livestock farming in different ES. In short, we study its influence on: (i) the landscape structure and diversity; (ii) the production of pasture; (iii) fire control; (iv) soil organic carbon sequestration; (v) hydrological connectivity and surface runoff. Our working hypothesis is that depopulation and land abandonment has a negative effect on the supply of pastures and regulating ES, while moderate intervention on the landscape increases some supply services (pasture and water, in particular) and improve other regulating ones (landscape structure, fire control and soil organic carbon sequestration).

2. Study area

The study area is the Leza valley in the north-western sector of the Iberian System. It covers an area of 297.8 km^2 and includes 12 municipalities (Fig. 1). The Leza valley is representative of the Mediterranean mid-mountains, with altitudes ranging between 600 and 1800 m a.s.l. The lithology is mainly Mesozoic quartzites, sandstones and limestones (Tischer, 1966). The relief is hilly with gentle slopes (gradients between 20 % and 40 %) which favoured agricultural use in the past, while the valley bottom and the fluvial terraces cover a very small surface area (García-Ruiz and Arnáez-Vadillo, 1991). Cuadrat and Vicente Serrano (2008) classify the climate as Mediterranean mountain. Annual precipitation ranges between 600 and 1000 mm per year, depending on the altitude and exposure, with over 60 % recorded in autumn and spring, and dry summers. The mean temperature is 11 °C at 600 m a.s.l., and 6 °C at 1800 m a.s.l.

The hilltops are dominated by forests of *Fagus sylvatica* and *Quercus pyrenaica*, while *Quercus rotundifolia* spp. *ballota* grows on the lower slopes. Some slopes are covered by pines following afforestation between the 1960s and 1980s (Ortigosa, 1991). The shrubs *Genista scorpius*, *Thymus vulgaris*, *Salvia rosmarinus* and *Buxus sempervirens* dominate limestone areas, while *Cistus laurifolius* is mainly found in siliceous areas (Arnáez et al., 2009).

The Leza valley was farmed intensively in the past, giving rise to a landscape strongly marked by humans and where hardly any natural forests were preserved. From the 12th century, land was deforested for pastures (Gil-García et al., 1996) to feed the transhumant flocks in summer: in the second half of the 17th century, 200,000 sheep were estimated to graze in the valley in summer (Ochagavía, 1957). In the 18th and 19th centuries, many marginal hillsides with gradients between 20 % and 40 % and, poor and very stony soils, were ploughed to grow cereals to feed the local population (Gómez Urdañez, 1986), accounting for 42.9 % of farmland in the region in the first few decades of the 20th century (Lasanta et al., 2009b).

Much of the population emigrated in the first half of the 20th century, when numbers fell from 7638 inhabitants in 1842 (25.6 pers./km^2) to 601 in 2022 (2 pers./km^2), farmland was abandoned (at present, not even 1 % of the area is worked) and livestock numbers fell sharply, especially sheep and goats, which stood at 30,000 head in 1950 and only 5252 in 1993, which gave rise to a vigorous process of plant succession (Arnáez et al., 2009).

In this context of abandonment of the primary sector, the regional administration set up a Plan for Shrub Clearing (PSC) in 1986 in order to promote regeneration of pasture and control the fire risk. The cost was borne by the Spanish government (38.8 %), the La Rioja regional government (33.5 %) and the European Union through the FEADER (27.7 %). In the Leza valley, 6551 ha were cleared between 1986 and 2021 (35.8 % of the shrub cover, or 21.9 % of its spread); in the first few years, a very small part, so that between 1986 and 1998 only 301 ha (4.6 % of the cleared area) was clear, whereas since 1999 this process increased considerably (6250 ha, an average of 297.6 ha/per year) (Cortijos-López et al., 2023a, 2023b).

Shrub clearing is carried out in selected areas by mechanical means (Fig. 1D), following strict rules (Lasanta et al., 2015, 2022), which include that each municipality can clear a maximum of 2 ha for each Livestock Unit (LU) in 5 years, taking 1 LU to be 1 cow or 1 horse, and 10 sheep or 10 goats, in order to force the animals to graze in the cleared areas and thus control the spread of shrubs. To create a mosaic landscape, with areas of pasture, shrubs and forest (Fig. 1C), the PSC laid down certain rules: 1) a maximum of 10 adjoining hectares can be cleared, leaving at least 2 ha uncleared; 2) slopes with a gradient of >30 % cannot be cleared to prevent erosion; 3) the former edges of crop fields

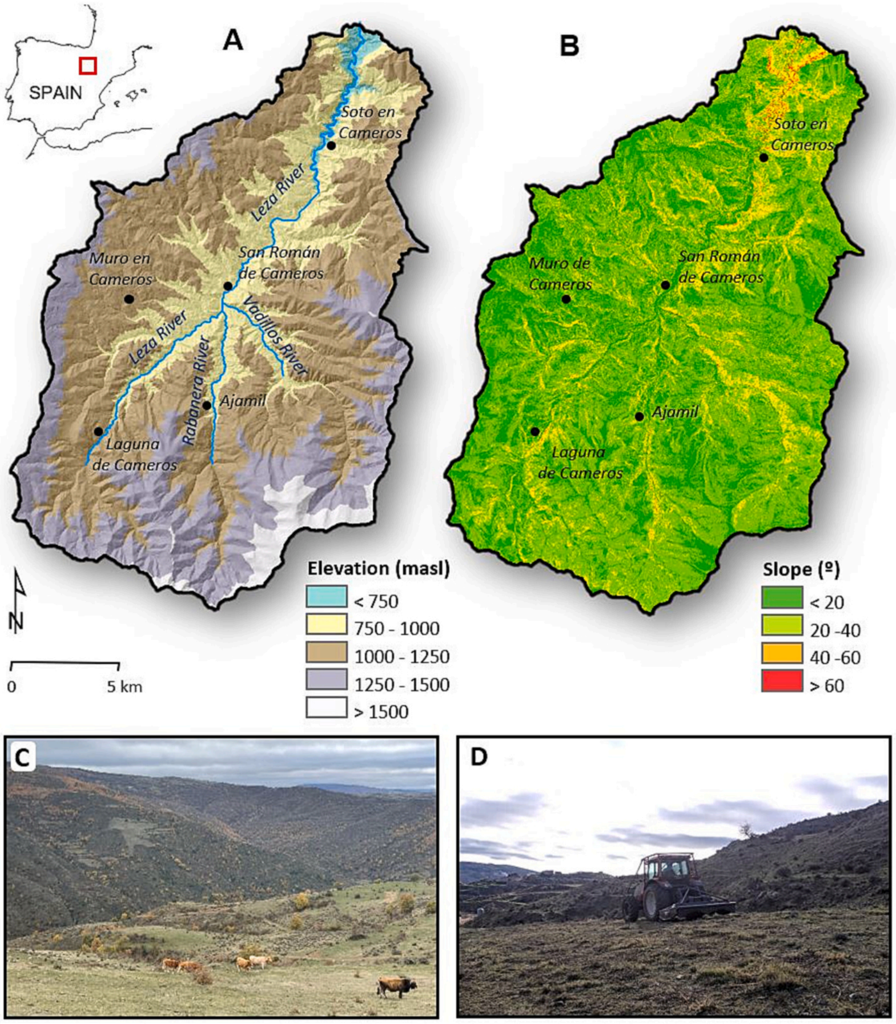

Fig. 1. (A) Location of the study area and digital elevation model. (B) Slope gradient map of the Leza Valley. (C) Mosaic landscape and livestock. (D) Shrub clearing practices.

must be left with natural vegetation to provide ecological corridors and diversity to the landscape; 4) clearing must be done at different altitudes to supply pasture at different times and avoid large homogeneous patches; 5) ecotones must be promoted, so that a strip of shrub land is kept between the forest and pasture created after clearing; 6) in the cleared areas, straight edges must be avoided to soften visual impact; 7) bushes and trees over 1.5 m high must not be removed during clearing, in order to create shade for the livestock and promote biodiversity. The remaining rules in the PSC deal with environmental issues, such as how to prevent soil erosion, protect fauna and promote biodiversity (Lasanta et al., 2016a, 2022).

3. Methods

Information was collected from several sources using various techniques and applied at different spatial and time scales (see Table 1), as detailed in the articles cited with the description of the method.

3.1. Landscape fragmentation and structure analysis

The municipality of Muro en Cameros was chosen to analyse the landscape fragmentation and heterogeneity, as it is representative of the changes in land use and land cover (LULC) and of applying the PSC, since it contains 5.6 % of the study area and 6.4 % of the cleared land. Aerial photography (1:18,000) was used to map the LULC in 2001 and information on shrub clearing between 2001 and 2007 was taken from maps. The study was reduced to the period available from official mapping of the clearing from the Council of Agricultura, Ganadería, Mundo Rural and Medio Ambiente (La Rioja Regional Government). The cleared areas were superimposed on the 2001 map, which showed the LULC before and after shrub clearing areas.

Various parameters were estimated from the databases using V-Late software (Vector-based Landscape Analysis Tools, extension for 10.0 of ArcGIS). The indices used to characterize landscape patterns between 2001 and 2017 are presented in Table 2. More information on the calculations can be found in Mandelbrot (1983), Lovejoy (1982), Kienast (1993) and Errea et al. (2007). To characterize the landscape heterogeneity, the three landscape ecology indices were calculated for diversity, evenness and dominance, based on the theory of information by Shannon and Weaver (1962).

3.2. Production and quality of pasture

18 sample points were chosen to calculate the production and quality of pasture in cleared areas. These were former crop fields that were abandoned, and at the time of sampling were covered by shrubs: 9 dominated by *G. scorpius* and 9 by *C. laurifolius*. Four samples were taken at each point before and after clearing in spring, followed by chemical and bromatological analyses (Reiné et al., 2014). For each sample, a 1 m^2 (1 m × 1 m) square was cleared, with the biomass cut by shears (manually). The cut grass was put into a plastic bag and weighed with a dynamometer. It was then transferred to the IPE-CSIC laboratories to estimate the production and nutritional value (quality and digestibility) of the cut grass, for which information was obtained from: the dry material, the cellular content, the neutral detergent fibre, acid fibre detergent, hemicellulose and lignins. The percentages of each of the above components and a system of mathematical equations determined the productivity of the forage. The specific methodology can be found in Lasanta-Martínez et al. (2013) and Reiné et al. (2014). Statistical analysis (ANOVA) were carried out to test if there are differences before and after shrub clearing.

Table 1
Summary of services, methods and periods of measurement.

Ecosystem service (ES)	Materials and methods	Periods of measurement
Landscape	Aerial photography and digital LULC cartography. V-Late software	2001–2017
Production and quality of pasture	Field and laboratory work	
Livestock numbers	Official Databases	1950–2022
Fire	Official databases	1968–2022
Cleared land	Official databases	1986–2021
Soil Organic carbon (SOC)	Random selection on field based on landowner and stakeholders, field work and aerial photographs. Laboratory analyses.	2021–2022
Hydrological connectivity	Connectivity Index (IC)	1956–2021
Surface runoff	RHESSys model	Calibration (2006–2010) Validation (2011–2015)

Table 2
Landscape metrics and indices used in the study.

Analysis	Variable	Abbrev.
Area	Total surface area (ha)	–
	Cleared area (ha)	–
	Number of patches	NP
	Number of cleared patches	NPD
	Average cleared patch (ha)	TMMD
	Average patch size (ha)	MPS
Borders	Edge density (m/ha)	ED
	Total length of edges (Km)	TE
	Mean patch edge (m)	MPE
Shapes	Mean shape index	MSI
	Perimeter-area ratio	MPAR
	Fractal dimension	MFRACT
Diversity (Shannon and Weaver, 1962)	Shannon index	IS
	Evenness index	Ev
	Dominance index	Dom

The values obtained are expressed in Forage Units (FU) or Alimentary Units (AU). An AU is the net energy produced by 1 kg of barley, equivalent to 7.61 mj/kg (Martín Bellido et al., 1986). It is estimated that 1 LU in the study area needs 8.2 AU/day or 62.40 mj/day (Ascaso, 1990), which provides information on the carrying capacity allowed by a plot before and after clearing (Martín Bellido et al., 1986).

3.3. Information on livestock numbers

To analyse the evolution of livestock numbers, information was taken from official statistics from the National Institute of Statistics (1950 and 1961), the Provincial Historical Archive of La Rioja (1972 and 1993), and the County Agricultural Office (OCA) of San Román de Cameros (2007 and 2022).

3.4. Evolution of the numbers of the surface fire spread and cleared land

Information on fires (number of fires, surface fire spread and its cover) recorded in the Leza valley was obtained from the Council for Sustainability, Ecological Transition and Regional Government Spokespersons (La Rioja Regional Government) for the period with available information: 1968–2022.

The Council also provided data on the area cleared annually in the municipalities of the Leza valley from the start of the PSC (1986) to the latest date with information (2021).

3.5. Soil organic carbon sequestration

Soil organic carbon (SOC) storage in soil was tested by taking samples in five LULC on both acid and alkaline environments (both environments were classified according to the bedrock and the typical vegetation communities that allowed us to differentiate the areas prior to pH laboratory analysis). The points selection was based on different information sources, such as consultation with landowners and stakeholders, field work and aerial photographs. In each LULC at least 3 samples were taken in sites chosen at random, with each one sampled at three points, and all combined to give compound samples (168 in total), up to 40 cm deep. The selected sites were: (i) shrub land (SH), with both *C. laurifolius* and *G. scorpius*, which represent the natural revegetation process following abandonment of land not grazed by livestock; (ii) young pasture (YSC) <5 years after shrub clearing; (iii) medium age pasture (MSC), 15 years after shrub clearing; (iv) old pasture (OSC), over 25 years after shrub clearing; and (v) control pasture (CP), areas that were grazed for centuries and which, therefore, can be considered as natural pasture; they represent the final stage of areas cleared and grazed periodically.

Soil analyses were carried out. Bulk density (BD) was estimated by oven drying the unaltered samples at 105 °C for 24 h. The organic material (OM) in the soil was measured using the loss on ignition method (at 375 °C); the total carbon (C) was determined by dry combustion in the Elementar Vario Max analyser; Carbonate concentration ($CaCO_3$) was determined using the Bernard calcimeter method, from which also the total inorganic carbon was calculated; soil organic carbon (SOC) was calculated by subtraction of total inorganic carbon (Cinorg) from the C and SOC stocks were expressed in Mg ha^{-1}.

3.6. Hydrological connectivity and surface runoff models

In order to estimate the effects of shrub clearing on surface water resources a hydrological connectivity and an ecohydrological model were applied in a sub-catchment (4 km^2) of the Leza valley. This sub-catchment underwent an initial increase in vegetation cover due to rural abandonment during the beginning of the second half of the 20th century, and from the end of the 20th century active management has been applied through shrub clearing.

Both models were parameterized from: (i) Topographic data extracted from the LiDAR-derived Digital Elevation Model at 2 m spatial resolution from the Spanish National Geographic Institute (CNIG) within the PNOA program. (ii) Data on land use obtained from aerial images for the years 1956, 2001 and 2021 (CNIG). The period 1956–2001 aims to represent natural revegetation after rural abandonment, while the period 2001–2021 aims to capture the potential effects of shrub clearing. (iii) Available historical series of precipitation and temperature (1962–2019) obtained from the Spanish Meteorological Agency (AEMET). These data were only used for the application of the ecohydrological model. Hydrological connectivity was modelled from the Connectivity Index (CI) developed by Cavalli et al. (2013) based on the original approach of Borselli et al. (2008), while the hydrological response was simulated using RHESSys (Tague and Band, 2004), which is a physical eco-hydrological model about SOC/N and water fluxes and it has been run in several basins all around the world (Chen et al., 2020). The calibration and validation processes were done under MonteCarlo procedure with satisfactory and very good results (Moriasi et al., 2007) (see Fig. 2). For further details about the methodology see Llena et al. (2023).

4. Results

4.1. Landscape fragmentation and structure analysis

Fig. 3 shows the LULC changes between 2001 and 2017 in the municipality of Muro de Cameros. The most important one is the increase in pasture by 350.6 ha, so that grazing land covered 0.4 % of the municipality's surface area in 2001 and 22.3 % in 2017, as a result of clearing about 350.6 ha (Fig. 4). Fig. 4 shows that the new pastures were pasture with shrubs and shrubs with pasture in 2001. Another important change is that, in 2017, the most extensive land cover (516 ha, 32.2 %) was broadleaved forest, which did not exist in 2001; a large part (472.8 ha) of broadleaved trees with shrubs have taken another step in plant succession toward becoming forest, with the rest remaining as broadleaved trees with shrubs. Moreover, some shrubs found in 2001 now forms part of the shrubs with broadleaved trees cover. Five LULC have not changed classification between the two dates (see Table 3).

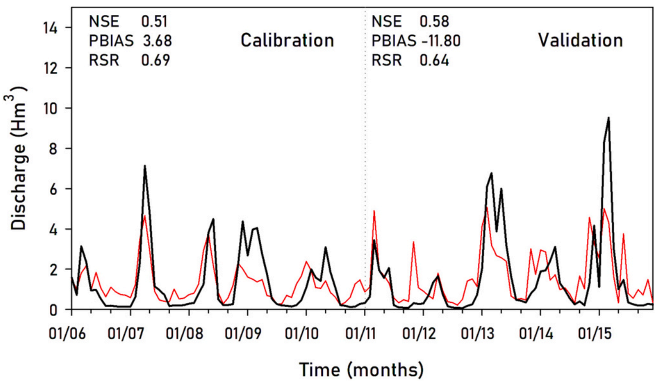

Fig. 2. Calibration and Validation statistics for Leza valley simulations. Red line: simulated discharge. Black line: observed discharge.

Table 3 gives information on the landscape structure and diversity in 2001 and 2017. It can be seen that NPT has sharply increase (27 in 2001 and 60 in 2017), which affects MPS (59.3 ha in 2001 and 26.7 ha in 2017). The largest NPT means the ED has increased (77.4 m/ha and 112.2 m/ha in 2001 and 2017, respectively) and TE (123.9 km in 2001 and 180 km in 2017) while, logically, MPE has decreased between both dates. Results on landscape geometry show small changes, with slight decreases in MSI, MPAR and MFRACT. Landscape heterogeneity highlights the notable increase in IS (1.534 in 2001 and 1.744 in 2017) and Ev (0.598 and 0.702 in 2001 and 2017, respectively), and the logical decrease of Dom (0.964 and 0.741 for both dates).

4.2. Pasture supply following shrub clearing

Table 4 includes information on the potential for forage in plots before and after clearing. It shows that production is always higher in alkaline, rather than siliceous, areas. Average production in fields of *G. scorpius* is 6666 Mj/ha compared to 2435 Mj/ha in *C. laurifolius*. Clearing has almost doubled the yield in *G. scorpius* areas and four-times in those of *C. laurifolius*. These significant changes in production means that the stocking density of a gorse field was 0.29 LU/ha/yr before clearing, and 0.57 LU/ha/yr afterwards. With *C. laurifolius* the values are 0.11 and 0.43 LU/ha/yr, respectively. It is important to realise that the stocking density is theoretical before shrub clearing and real afterwards, since the livestock cannot reach the pasture under the shrubs as these make grazing difficult or impossible.

4.3. Evolution of livestock numbers

Fig. 5 shows how livestock numbers changed in the Leza valley between 1950 and 2017. The LUs decreased between 1950 and 1972 and then increased by almost 3.5-fold in 2022 compared with 1972. The most important change was with cattle, which only numbered 555 in 1950, and 4612 in 2022; there was a steady rise in the 1970s, increasing by 4.7-fold between 1972 (983 head) and 2022 (4612 head). On the contrary, goat numbers dropped sharply from 12,575 in 1950 to 413 in 2007, before recovering very slightly in 2022 (786). Sheep, the basis of traditional livestock farming, fell drastically in number between 1950 (17,379) and 1993 (2826) to partially recover in recent years. Horses followed the same trend as sheep, with it being very noteworthy that in 2022 the number (1035) was almost the same as in 1950 (1219), with an important difference: they were originally used for farm work but now are produced for meat.

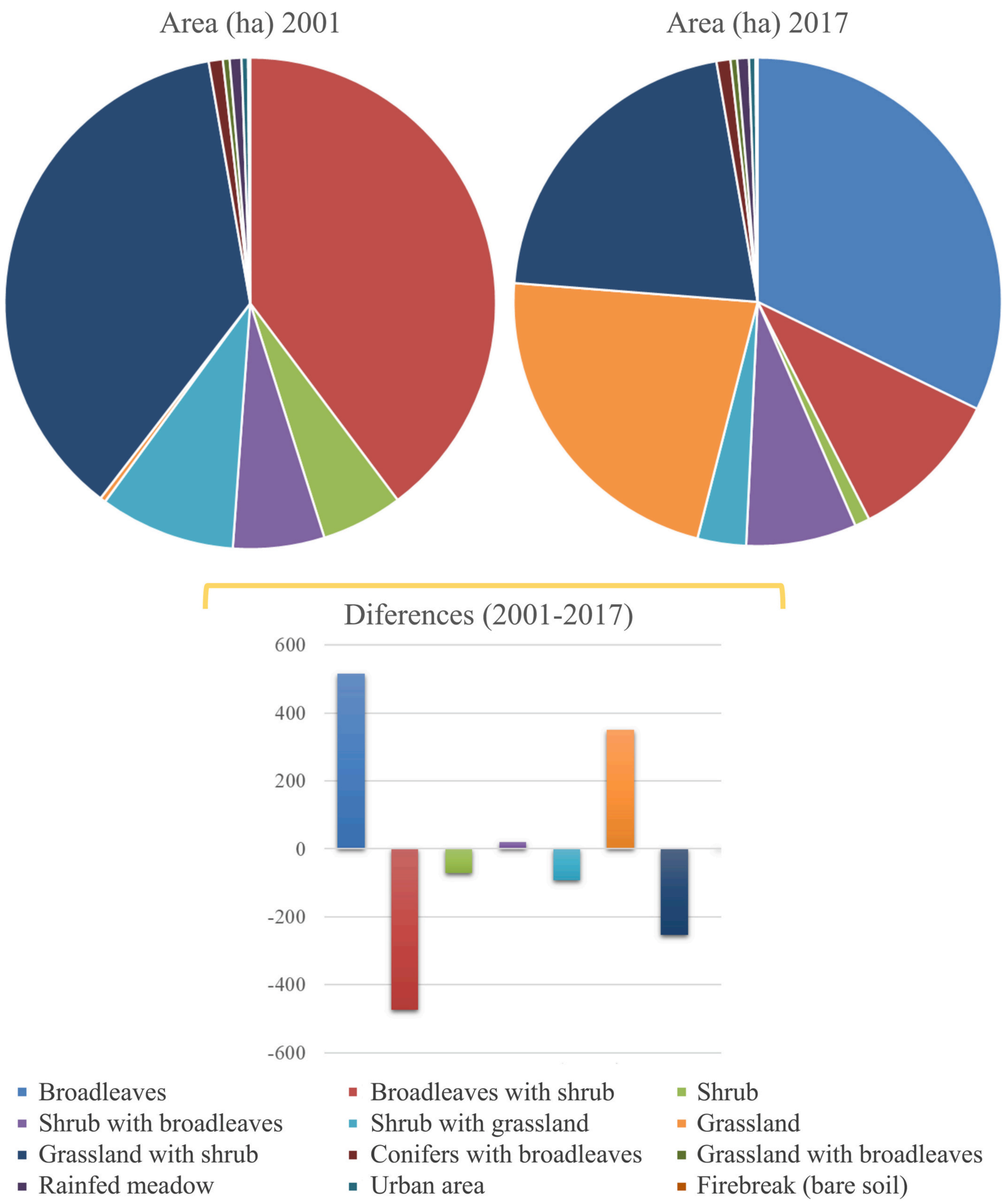

Fig. 3. Land use and land cover changes in the municipality of Muro between 2001 and 2017.

4.4. Evolution of number of fires and surface fire spread

Fig. 6 shows the evolution of the burned area and the cleared area. The first fire recorded in the database took place in 1968, when 16.9 ha were burned. Between 1968 and 1977 there were years without fires (1969, 1970, 1974 and 1977) with the rest recording small ones, as the burned area is very small (10.8 ha in 1975 the maximum value). Between 1978 and 1985 there were fires every year, with a clear upward

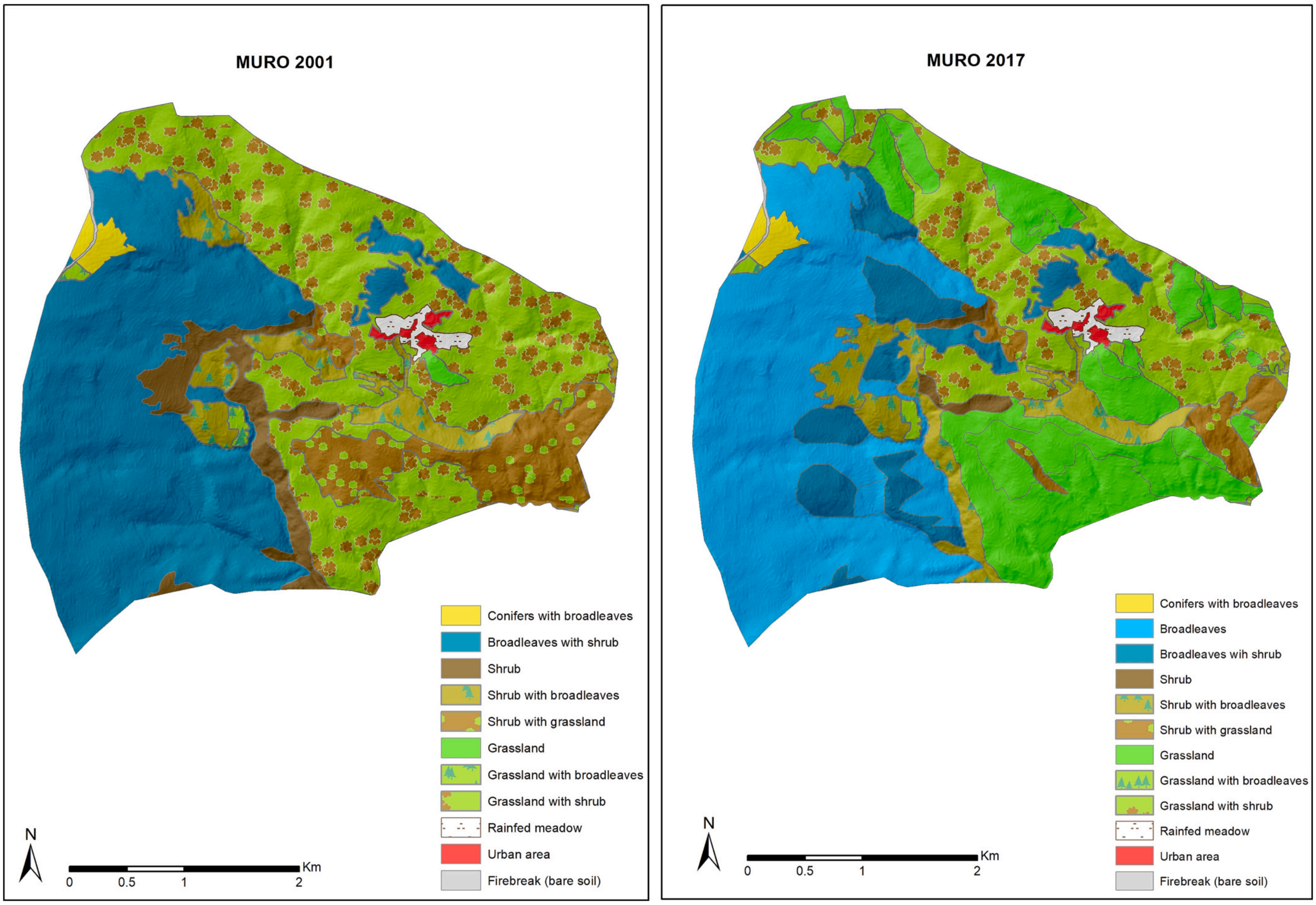

Fig. 4. Land use and land cover change (2001–2017) in Muro de Cameros (Leza valley). Own source and creation.

Table 3
Landscape metrics and ecology indices (2001–2017) in Muro de Cameros (Leza valley).

Analysis	Variable	Abbrev.	2001	2017
Area	Total surface area (ha)		1601.5	1601.5
	Cleared area (ha)			350.6
	Number of patches	NPT	27	60
	Number of cleared patches	NPD	0	17
	Average cleared patch (ha)	TMMD	0	20.6
	Average patch size (ha)	MPS	59.3	26.7
Borders	Edge density (m/ha)	ED	77.4	112.2
	Total length of edges (Km)	TE	123.9	180
	Mean patch edge (m)	MPE	4589.5	2999.7
Shapes	Mean shape index	MSI	2.178	1.928
	Perimeter-area ratio	MPAR	0.037	0.032
	Fractal dimension	MFRACT	1.356	1.34
Diversity (Shannon and Weaver, 1962)	Shannon index	IS	1.434	1.744
	Evenness index	Ev	0.598	0.702
	Dominance index	Dom	0.964	0.741

Table 4
Production and carrying capacity in areas of *G. scorpius* and *C. laurifolius* before and after clearing. Significant differences between production in both communities were recorded at level $p < 0.01$.

Community		Production (Mj/ha)	Carrying capacity (LU/ha)	Surface area (ha)*
Genista scorpius	Before clearing	6666	0.29	3.4
	After clearing	12,983	0.57	1.8
Cistus laurifolius	Before clearing	2435	0.11	9.4
	After clearing	9741	0.43	2.3

Surface needed to feed 1 LU throughout the year.

trend and some years when large areas were burned (45.3 ha in 1978; 84.6 ha in 1981; 150 ha in 1983 and 145.5 ha in 1985). In the 18 years between 1968 and 1985, 614.4 ha were burned. From 1986, at the same time as the PSC was put into action, the burned area decreased drastically so that in the 37 years between 1986 and 2022, only 45.5 ha burned. In 31 of the 37 years (see Table 1 Supplementary material) there were no fires or <1 ha was burned. Only in 1989 there were various fires that burned a total of 25.5 ha. A point to emphasize is that, since 1997 no fires have been recorded, only the beginnings, quickly extinguished. The surface fire spread since 1986 consists of 25.6 % of forest and 74.4 % open land (Table 1 Supplementary material).

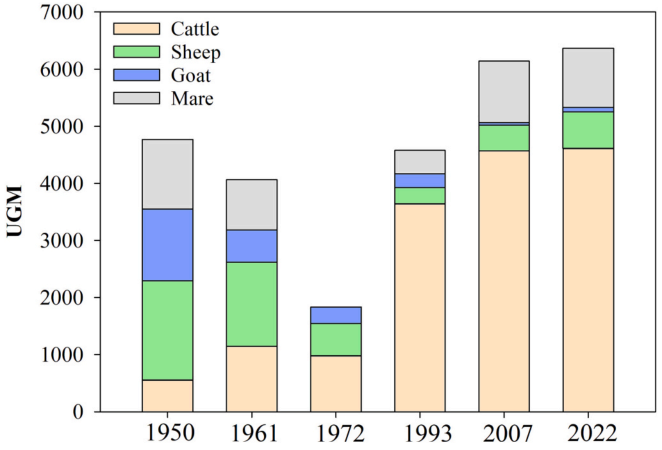

Fig. 5. Evolution of livestock numbers in the Leza valley (1950–2017). Source: 1950 and 1961: Statistical Overview of Agriculture from the Provincial Department of Livestock Development; 1972 and 1993: Chamber of Agricultural, information taken from the Provincial Historic Archive; 2007 and 2022: County Agricultural Office of San Román de Cameros (Regional Government of La Rioja). Own creation.

4.5. Soil organic carbon sequestration in areas cleared at different times

Fig. 7 shows SOC stocks in siliceous and alkaline areas in various LULC. The stock of total SOC fluctuates between 86.9 Mg ha^{-1} (YSC) and 113.0 Mg ha^{-1} (CP) in acidic soils, and between 113.8 Mg ha^{-1} (SH) and 176.7 Mg ha^{-1} (OSC) in alkaline areas. The overall profile shows: (i) more SOC is found in alkaline, rather than acidic soils, whatever the LULC; (ii) shrub clearing to regenerate pastures generally increases SOC, except in young shrub clearing on acidic soils: 103.3 Mg ha^{-1} in SH and 86.9 Mg ha^{-1} in YSC; (iii) SOC increases with the age of clearing in both types of lithology: YSC < MSC < OSC (with similar values in MSC and OSC in acidic soils); (iv) in alkaline soils OSC shows the highest values of all LULCs (176.7 Mg ha^{-1}), while in acid soils OSC (109.1 Mg ha^{-1}) and CP (113.0 Mg ha^{-1}) have the highest LULC values; (v) OSC has much greater SOC values than SH in alkaline areas. Taking the classification between acid and alkaline soils into account, significant differences can be seen in YSC, MSC and OSC. There were also large differences within the same depth between the various LULC. Lastly, taking the SOC samples as a whole, SH and YSC were found to be very different from MSC and OSC.

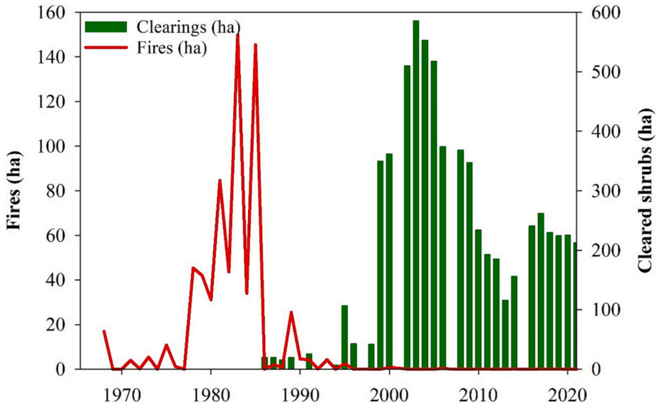

Fig. 6. Evolution of the burned area (1968–2022) and cleared area (1986–2021) in the Leza valley. The burned area is in red and the cleared area in green.

4.6. Surface water resources: Hydrological connectivity and runoff.

Fig. 8 shows the main results of hydrological connectivity (Fig. 8B and C) and surface runoff modelling in response to the main land use changes undergone by the study sub-catchment during the period 1956–2021 (Fig. 8A). Through the first period, due to the increase of vegetation cover after rural abandonment (mainly shrub encroachment), the study area underwent a decrease in the degree of hydrological connectivity (0.03 median decrease) following a negative trend in surface runoff. After 2001, due to the active management strategies of the La Rioja Government through shrub clearing, hydrological connectivity increased (0.02 median increase) while the runoff coefficient rose significantly (14 % increase of the median in respect of the previous study period).

Results show that the degree of surface hydrological connectivity (structural connectivity) is related with surface runoff (functional connectivity), in the way that an increase or decrease of the former implies an increase or increase of the latter (Fig. 8C and D).This relation will be largely determined by the pattern and distribution of the mosaics of different land uses (landscape configuration), as well as by its changes over time.

5. Discussion

Mountains provide important ES to the neighbouring regions, such as the water supply, carbon sequestration, grazing and timber resources, leisure activities and numerous cultural values, among others (Grêt-Regamey et al., 2012; Lavorel et al., 2017). However, the supply of ES is highly dependent on landscape management: Lavorel et al. (2017) found that, in the French and Austrian Alps heterogeneous landscapes provided more diverse ES than homogeneous ones caused by land abandonment. In several alpine landscapes in Switzerland, Austria and Italy, there has been a reduction in agricultural goods services since the 19th century, while those of regulation, such as water resources, water quality, land conservation and carbon sequestration have increased, with no clear trend seen in cultural services (Schirpke et al., 2013; Bürgi et al., 2015; Egarter Vigl et al., 2016). However, in the Mediterranean mountains, the reduction in supply services is compensated by improved heritage and cultural ones (Morán-Ordoñez et al., 2013; Locatelli et al., 2017; Bruno et al., 2021).

The shrub clearing - livestock grazing pairing involves the creation of a mosaic landscape with more fragmented patches (smaller, less regular in shape and of various types), and an increase in diversity and fewer dominating features. The creation of pastures among the shrubs and forests reduces landscape homogenization (large patches with little diversity of land uses and covers), which is the usual result of land abandonment in the mountains of Europe in recent history (MacDonald et al., 2000; Mottet et al., 2006; Bracchetti et al., 2012; García-Ruiz and Lana-Renault, 2011). Likewise, the literature does not agree on the consequences of landscape changes resulting from land abandonment on species diversity. Some authors state that revegetation and homogenization of the landscape after land abandonment is negative with respect to species diversity, because management practices are lost and species adapted to cultural landscapes and mosaic landscapes disappear (Suárez-Seoane et al., 2002; Cohen et al., 2011; among others). Other authors, on the contrary, conclude that revegetation of abandoned lands, especially if the forest phase is reached, is positive for biodiversity (Rey-Benayas et al., 2010; Navarro and Pereira, 2012; Regos et al., 2016, among others).

On the other hand, shrub clearing creates a mosaic landscape with tree formations, shrub and pasture together in the territory. The public values this landscape, which can promote tourist activities and a complementary source of income. Thus, Sluiter (2005) pointed out that traditional landscapes are very attractive to tourists and visitors because of the mosaic of land uses and land covers. Benjamin et al. (2007) observed that most of the public views abandoned unused land

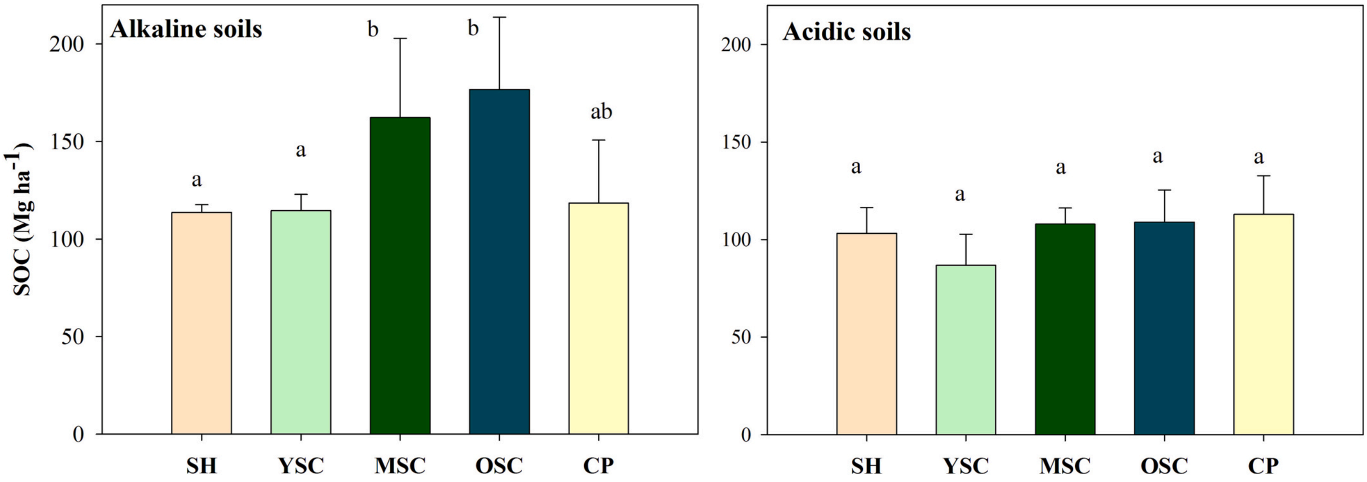

Fig. 7. SOC stocks throughout the soil profile for the different land uses and land covers (0–40 cm). Note: SH, shrubland, YSC young shrubland clearing, MSC medium shrubland clearing, OSC old shrubland clearing, and CP Control pasture. (A): Acidic soils and (B) Alkaline soils. Means with different letters are significantly different at 0.05 level of significance ($p < 0.05$).

negatively. Sayadi et al. (2009) found that recovering abandoned fields helped to improve the aesthetics and attractiveness of the landscape for tourism, since it increased the heterogeneity of the land cover and biodiversity.

This confirms our hypothesis that moderate intervention in selected areas, by shrub clearing and extensive livestock, gives positive results for (i) the supply of pasture, (ii) increased numbers of livestock, (iii) control of forest fires, (iv) improve soil organic carbon stocks, and (v) improved connectivity and quantity of water resources. In addition, it complies with the objectives in PAC 2023–2027 (PEPAC, 2023).

Shrub clearing improves access for livestock to the grazing below the shrubs, consisting of grasses and legumes with a high forage value (Lasanta et al., 2019). The pasture supply increases considerably: before clearing, 3.4 ha of *G. scorpius* fields were needed in theory, and 9.8 ha of *C. laurifolius* to feed 1 LU, whereas this was reduced to 1.8 and 2.3 ha, respectively, after clearing. The increase is considered to be theoretical because, in fact, the pasture was not fully used before clearing, since the shrubs hindered access to the grasses below. Therefore, production prior to clearing is potential, as it was not eaten by the livestock. In reality, shrub clearing means that changing a space from useless to being able to feed 0.57 LU/ha in areas formerly covered by *G. scorpius* and 0.43 LU/ha for *C. laurifolius.* Cleared areas also help livestock to use other spaces in the pasture paths between cleared zones. Valdelvira and Balcells (1986) found that the cleared areas in the Spanish Pyrenees acted as points of attraction (or bait) for the livestock, which consume forage in nearby land as they move, but would not go there without the attraction of cleared shrubs. In this way, they indirectly help to increase the supply of pasture (Lécrivain and Beylier, 2004).

The larger supply of grazing has led to a rise in livestock numbers from 1834 LU in 1972 to 6365 LU in 2022, meaning an increase of almost 3.5-fold in 50 years. Lasanta et al. (2019) point out that, for the same study area, the number of livestock farms fell from 125 in 1972 to 60 in 2017, but grew in average size: 27.6 LU in 1972 and 115.2 LU in 2017. These changes are similar to those recorded in other parts of the Mediterranean mountains, which can be explained by the CAP subsidies for extensive livestock farming, which make medium and large farms viable, while it is not sufficient for small ones, so they disappear (Veysset et al., 2005; Lasanta and Laguna Marín-Yaseli, 2007). Nevertheless, shrub clearing must have been a great help in the current situation, as the increased supply of pasture reduces the amount of feed that farmers have to buy to supplement grazing. A recent report drawn up by the LIFE MIDMACC project in the Leza valley concluded that clearing saved farmers 855€ per LU per year (Goetz et al., 2022). On the other hand, it must be remembered that the average size of the farms is much larger in the study area (115.2 LU) than in Spain as a whole (53 LU), which is an important factor for the sustainability of farms (MARM, 2010). Lasanta et al. (2019) also state that shrub clearing has contributed to the addition of young farmers, some of whom had no ties to farming before coming to the Leza valley.

The Food and Agriculture Organization of the United Nations (FAO, n.d.) defines cultural services as non-tangible assets that people obtain from ecosystems, consisting of cultural identity, a sense of belonging to the region, aesthetic inspiration and spiritual experience. In this respect, the PSC has proved to help maintain the traditional, or mosaic landscapes. Mosaic systems not only promote that aesthetic attractiveness of the area for activities such as tourism, but also offer a symbol of identity and promote a feeling of belonging with traditional pursuits that have been passed down from generation to generation. Even people from outside this historic background can feel part of the surroundings by helping to maintain these activities (Hunziker, 1995; Benjamin et al., 2007; Lasanta et al., 2016b). Lasanta et al. (2019) verified this by observing that about 77 % of the farms in the Leza valley belonged to people born in or with historic ties to the area. It is also very attractive to people from outside, who proactively contributed to extensive livestock farming with larger than average numbers of livestock units.

There has been a huge fall in the burned area since 1986. Without doubt, improvement in detection systems and firefighting methods have helped as it occurs in other Mediterranean areas (Rodrigues et al., 2016; Turco et al., 2016; Urbieta et al., 2019). However, the reduction in the burned area is much greater in the Leza valley and in the mountains of La Rioja as a whole, than in other parts of the Mediterranean as a result of preventative policies carried out there since 1986 (Lasanta et al., 2018). The combination of shrub clearing with extensive livestock farming lowers the burned area for three reasons: (i) by eliminating the biomass, since the cleared areas change from Rothermel (1983), with a highly flammable fuel load of 10–15 tn/ha, to model 1 in which the land is covered in pasture (1 tn/ha load). In Mediterranean regions, eliminating fuel is very necessary to control fires, as there are frequent droughts and electric storms, very likely conditions to cause forest fires (Fonseca et al., 2017). Therefore, prevention policies aim to eliminate fuel by shrub clearing, prescribed burning, mechanical means, grazing, etc. (Fernandes et al., 2013; San Emeterio et al., 2016; Fonseca et al., 2017). (ii) By changing a homogeneous landscape of mainly shrubs, into a more diverse one of a mosaic of pasture, shrubs and forest, and more fragmented - a larger number of smaller patches. It is well known that a continuous cover of flammable material considerably increases the fire risk and makes firefighting difficult, whereas more fragmented landscapes with different LULCs reduce the risk (Viedma et al., 2009;

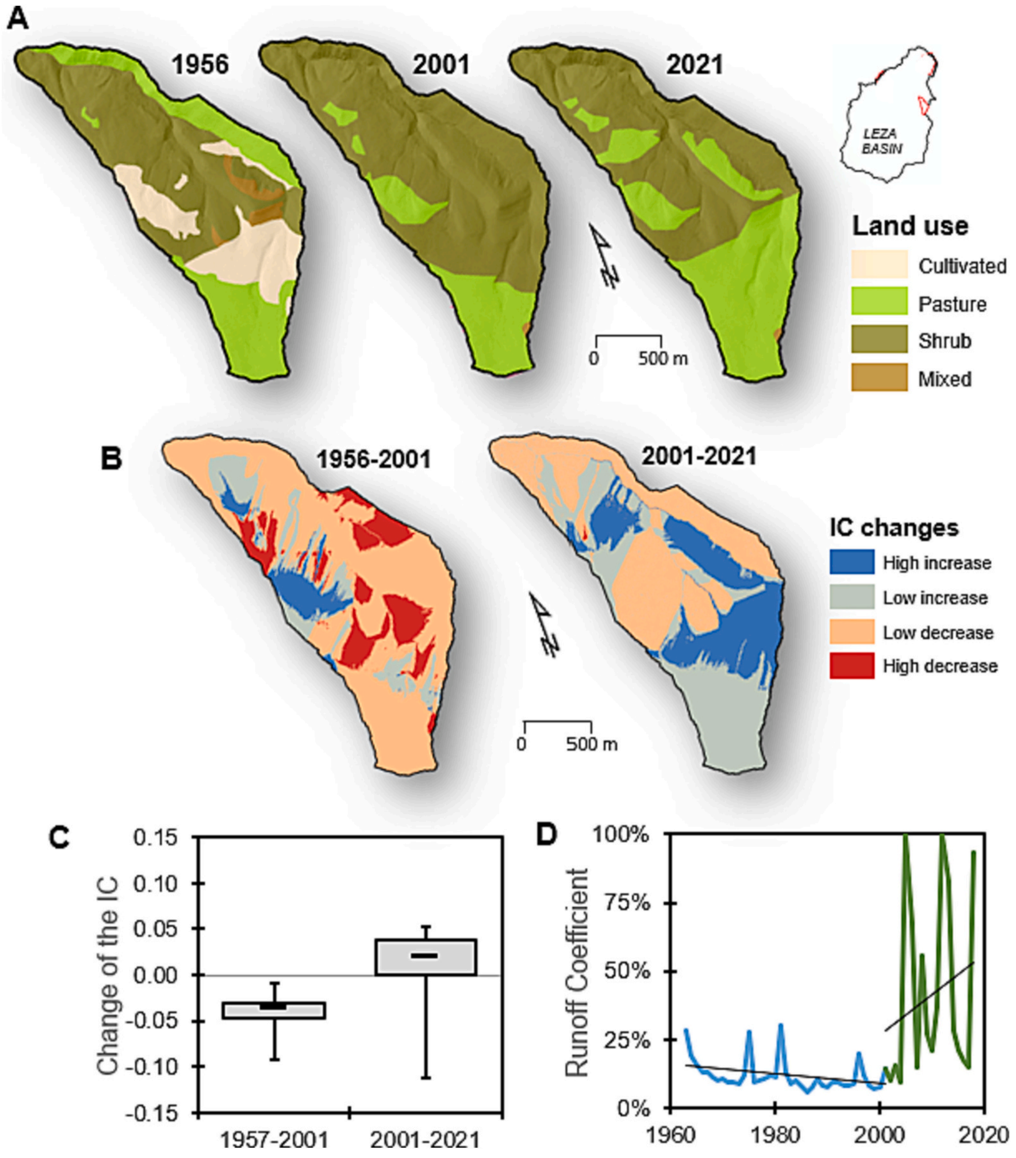

Fig. 8. A. Land use maps obtained from the mapping of aerial photographs in the archives. B. Differences in Connectivity Index (CI) maps. C. Boxplots of the differences between Index of Connectivity (IC) maps. Centre line of the box represents median value, while bottom the D25 and the top D75, lower whisker represents the D5 and the upper D95. D. Runoff Coefficient values estimated by the RHESSys model: the blue line represents the vegetation increase period after abandonment (1956–2001), while the green line represents the shrub clearing period (2001–2021). Note that lineal trend is presented with a black line.

Moreira et al., 2011). In addition, frequent grazing contributes to maintaining a mosaic landscape by controlling plant succession (Lasanta et al., 2022). (iii) By losing interest in pasture fires. Pasture fires form part of the farming culture in the Mediterranean mountains; for thousands of years, fire has been a tool to regenerate pasture after burning shrubs and forests (Rius et al., 2009; Ruiz-Mirazo and Robles, 2012; San-Miguel-Ayanz et al., 2013; García-Ruiz et al., 2020). This last reason is the main factor explaining the drastic reduction in surface fires since the start of PSC (1986). With the PSC, there is no sense in burning shrubs because the council provides livestock farmers with free pasture. In addition, setting pasture fires is a highly punishable environmental offence, even with jail sentences (Lasanta et al., 2022).

This study also shows that pasture regeneration after shrub clearing is positive for soil organic carbon stocks by increasing 55.3 % in alkaline soils (SH = 113.8 Mg ha^{-1} and OSC = 176.7 Mg ha^{-1}) and 5.6 % in siliceous soils (SH = 103.3 Mg ha^{-1} and OSC = 109.1 Mg ha^{-1}). Some studies have shown that pastures contain similar SOC stocks to those of forests (Berninger et al., 2015; Nadal-Romero et al., 2018b, 2021), although others give slightly lower values (10 % less) in pasture than forests (Guo and Gifford, 2002). Pastures are considered to be good carbon sinks for several reasons: (i) due to the large quantity of underground biomass of fine roots whose rapid decomposition provides constant organic material compared to the lower amounts in shrubs (García-Pausas et al., 2017); (ii) Frequent grazing incorporates organic material from livestock excrement, something which does not occur in shrubs as they are not grazed; moreover, shrubs tend to reduce its underground biomass because some grasses whose survival depends on grazing disappear (Lanta et al., 2009; García-Pausas et al., 2011); (iii) the large amount of grasses in pastures increases the fine roots of underground biomass, which improves aggregates stability and helps to stabilise the SOC (Pohl et al., 2011; Guidi et al., 2014); (iv) also, shrubs provide low-quality leaf litter that takes longer to decompose and integrate into the soil (García-Pausas et al., 2017). On the other hand, pastures have a larger proportion of recalcitrant organic carbon (more than shrubs and coniferous) which suggests that grasses for pasture help to stabilise SOC (Nadal-Romero et al., Under review). It is interesting to note that changing shrubs into pastures is a good strategy to improve and restore soil quality, as well as increasing carbon sequestration. In short, it is a promising contribution on how the Mediterranean mid-mountains can help to mitigate climate change.

A result from this study that has also been shown in other studies, is that alkaline soils, which are sandier in texture and have a greater SOC storage capacity, contain more SOC than acidic ones, which have a higher percentage of clay (Li et al., 2016; Yang et al., 2020). In addition, Cortijos-López et al. (2023a, 2023b) state that alkaline soils have a greater density of grasses than acid ones, which determines the underground biomass. Pavinato and Rosolem (2008) explain the poorer grass cover in acid soils by their lower cation exchange capacity than in alkaline soils. Cation exchange capacity increases with pH, which means that essential nutrients like N, P, K, S, Ca and Mg are strongly retained in acidic soils, making it difficult for plants to grow (Hinsinger et al., 2003).

One of the main ES supplied by the Mediterranean mountains is water to the surrounding regions. It must be remembered that mountains behave like humidity islands or water towers (Viviroli et al., 2007), since they produce between 60 % and 80 % of the world's drinking water (Bento-Gonçalves et al., 2014). However, in Mediterranean areas, water resources have decreased in recent years because of a higher atmospheric demand for water (Vicente-Serrano et al., 2014), and reforestation, mostly linked to land abandonment in the mountains (Sluiter and de Jong, 2007; García-Ruiz and Lana-Renault, 2011). Giorgi (2006) considered the Mediterranean basin to be a “hot spot” on a global scale, due to the limitation of water resources. In addition, and at the same time, there is a sharp rise in the demand for irrigation (Beguería et al., 2022), and from the expanding population concentrated in the same space as industry and services (Rico-Amorós et al., 2009). Hence, water resource management and the availability of water are basic aspects in Mediterranean regions. To increase water resources, some authors have suggested regenerating pastures by eliminating shrubs, as the runoff coefficients are higher in a grass cover rather than shrubs. Nadal-Romero et al. (2013) observed in the Aísa valley Experimental Station (Spanish Pyrenees) that pasture regeneration following shrub clearing gave rise to increased surface runoff: in the study period (1991–2011) pastures produced an average of 96.2 l/m^2/year (runoff coefficient of 8.2 %) against 64.3 l/m^2/year (runoff coefficient of 5.5 %) in the dense shrub plot, with almost no increase in erosion (mean values of 69.7 g/m^2 and 41.5 g/m^2 in pasture in shrubs respectively). That means that shrub clearing is a positive action in water production, a very scarce resource in the Mediterranean, without causing unmanageable erosion problems for the system (Nadal-Romero et al., 2013).

The study area does not have information from experiments on the topic, but by applying the Connectivity Index and the RHESSys ecohydrological model, an estimate can be made on the effect of shrub clearing on surface water resources. The effect of vegetation on surface connectivity is mainly explained by the degree of associated roughness. The greater the vegetation, the greater the surface roughness, which causes more resistance to surface flow and, therefore, a reduction in potential connectivity. The decrease in connectivity due to the increase in vegetation after rural abandonment between 1956 and 2001 is also described by several authors in the context of the Mediterranean mountain basin (i.e., López-Vicente et al., 2016; Lizaga et al., 2016). For instance, Llena et al. (2019) observed that natural revegetation succeeded after abandonment in some areas of the Alto Cinca catchment (Southern Pyrenees) had a direct effect on the decrease in connectivity, while in some areas close to the valley bottoms there was an increase in connectivity due to its transformation from forested areas to agricultural crop fields after ploughing. Ploughing is a similar scenario to shrub clearing, but with an agricultural objective instead of extensive livestock.

Throughout the Leza valley, application of the RHESSys ecohydrological model suggests that surface runoff will rise by 9.7 % if the shrubs are cleared on 12.3 % of the basin surface suitable for clearing, according to the PSC criteria (Zabalza-Martínez et al., 2023). These results agree with those obtained in the Spanish Pyrenees. Khorchani et al. (2020) found that, in the experimental Arnás catchment (285 ha), mainly covered by succession shrubs after farming was abandoned, clearing 15.7 % of the shrubs increased annual runoff values by 16 %, reduced evapotranspiration (9 %) and soil moisture by (6 %).

In this research, we have highlighted some of the positive results obtained in ES after shrub clearing in Mediterranean mountains. Although, the PSC carried out by the Regional Government of La Rioja could be considered a regional (site-specific) management, it should be highlighted that mechanical shrub clearing has been used in the last decade in different Mediterranean areas, not only in Spain (i.e. Fontúrbel et al., 2016), but also in Italy (Jahdi et al., 2023), Portugal (i.e. Castro et al., 2022; Lecomte et al., 2022) or Israel (Bashan and Bar-Massada, 2017). We should also highlight some potential negative issues related to this landscape management. We have preliminary observed that some cleared areas are not used by farmers (those farthest from the municipalities), starting a new revegetation process after shrub clearing, resulting in negative economic investment. Also, some preliminary results suggest the concentration of extensive livestock in some points, favouring soil erosion and land degradation.

6. Conclusions

Shrub clearing eliminates biomass and creates a mosaic landscape in which areas of pasture alternate with shrubs and forests. The new landscape is more heterogeneous and fragmented. But above all, it is more sustainable that unmanaged, abandoned land, as the ES supply to the public is improved: grazing and water resources increase, the fire risk and burned area decreases, and there is a good potential for soil organic carbon sequestration (especially in alkaline environments) to improve adaptation to climate change. It is also a more functional landscape as it provides more forage, which is essential to expand livestock numbers and keep more livestock farms in action, thus reducing depopulation; in short, it contributes to local development of the Mediterranean mid-mountains.

In marginal areas where there are few alternatives for development, moderate intervention in the region, such as shrub clearing to regenerate pastures and help with extensive livestock farming, seems to be an appropriate strategy for local development and to provide better ecosystem services to the population as a whole.

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CRediT authorship contribution statement

Teodoro Lasanta: Conceptualization, Writing - Original Draft. **Melani Cortijos-López**: Formal analysis, visualization, Writing - Review & Editing. **Paz Errea**: methodology, software, Writing - Review & Editing. *Manel Llena*: methodology, software, Writing - Review & Editing. **Pedro Sánchez-Navarrete**: field work and Writing - Review & Editing. Javier Zabalza: methodology, software, Writing- Reviewing and Editing. Estela Nadal-Romero: Conceptualization, Formal analysis, Writing - Review & Editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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