RESEARCH ARTICLE

From the local landscape organization to land abandonment: an analysis of landscape changes (1956–2017) in the Aísa Valley (Spanish Pyrenees)

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Abstract

Context The Mediterranean mountains have witnessed the revegetation of former pasture and cultivated fields since the mid-20th century. The process started when the mountains joined a dynamic and competitive market, which led to depopulation, abandoning cultivated fields, and a reduction in extensive livestock farming.

Objectives We investigate changes in land use and land cover (LULC) and landscape structure in a valley of the Central Pyrenees in 1956, 1981 and 2017, and we discuss the implications for land management within a multidisciplinary context.

Methods Aerial photographs are used to map the LULC in 1956, 1981 and 2017, followed by landscape ecology metrics and indices to analyse the structure of the landscape.

Results The results show: (i) a reduction in cultivated area (-42%) and pastures (-63%) in the montane belt between 1956 and 2017, while forests doubled in area; (ii) changes in LULC are more significant in the montane belt than in subalpine and alpine areas; (iii) based on the Kappa index, it was found that the 29% of the area had undergone changes in LULC between 1956 and 2017, with the changes being greater in the first period (1956–1981) than in the second (1981–2017); (iv) the structure and heterogeneity of the landscape shows an increase between 1956 and 1981, and a change in trend from 1981 to 2017, so that the landscape is more homogeneous in 2017 than in 1956.

Conclusion The discussion suggests the need to maintain and recover mosaic landscapes, since their structure is akin to traditional cultural ones, to increase biodiversity and sustainability, and provide ecosystem services to the population.

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Introduction

The landscapes of the Mediterranean mountains are brought about by interaction between nature and people over hundreds or thousands of years to produce goods, so that many of them are considered to be cultural landscapes (Antrop 2005; Blondel 2006; Martínez de Pisón 2009; García-Ruiz and Lasanta 2018). Landscapes are conditioned by their *composition* (types of land use and land cover comprising the elements of the landscape) and their *configuration*

(spatial distribution of the types); taken together they provide the landscape structure (Burel and Baudry 2002; Varga et al. 2018). It is essential to know what the land use and land cover (LULC) has been over the centuries before the structure and evolution of the landscape can be analysed.

The LULC in the Pyrenees have changed greatly over the last century (Lasanta and Vicente-Serrano 2007). For thousands of years, the resources of the Pyrenees, as in other Mediterranean mountains, were exploited within the framework of a management model that had little interchange among the regions (García-Ruiz and Lasanta-Martínez 1990; González-Sampériz et al. 2019). The need to use their own resources to feed a large population and many livestock in the region meant that the whole area was geared toward production, meaning deforestation and the clearing of scrubland on several slopes in order to expand the cultivated area and pastures (Lasanta Martínez 1989; Montserrat 1992; García-Ruiz and Valero 1998; García-Ruiz et al. 2015). In addition, the forest was frequently felled for firewood and timber for construction and ships (Balcells 1983; De la Riva 1997; Varela et al. 2020).

Throughout the 20th century, especially from the 1950s to the 1980s, anthropogenic pressure declined due to the Pyrenees becoming part of an ever widening socio-economic system (first regional, then national and then international), in which the products reached a highly dynamic and competitive market (Daumas 1976; García-Ruiz 1976; Lasanta Martínez 2002). As a result: (i) large numbers of the population emigrated to the cities and industrial areas (Ayuda Bosque and Pinilla Navarro 2002; Molina Gallart 2002); (ii) cultivated fields were abandoned as they were not suitable for ploughing with tractors, with crops only remaining in the flat, fertile areas that could be accessed with farm machinery (Lasanta Martínez 1988, 1989); (iii) the number of livestock farmers fell, especially for sheep (García-Ruiz and Balcells 1978; Lasanta-Martínez 2005); (iv) the forest was no longer exploited, as the timber and firewood could not compete with the alternatives, but also because of a certain naturalistic concept of the environment, which viewed managing the forest as most unsuitable (Marraco and Rubio 1992; De la Riva 1997).

During the 20th century, full exploitation of the area's own resources to supply local demand, requiring management adapted to the strengths of each part of the landscape, changed to a system that marginalised (extensification or complete abandonment) of the slopes and intensification of the more fertile areas with good accessibility, in order to obtain competitive products for external markets (García-Ruiz and Lasanta 1993; Lasanta Martínez 2002). This started a process of revegetation, with rapid advances of scrubland and secondary succession forest which now cover most of the Pyrenees (Lasanta and Vicente-Serrano 2007), a process that will continue throughout the 21st century (Houet et al. 2017).

The severe changes in LULC involve a heavily altered landscape structure, affecting the environment, socio-economics and the supply of ecosystem services (González Díaz et al. 2019; Varela et al. 2020; Bernués et al. 2022). It must not be forgotten that the mountain areas are key suppliers of ecosystem services (Foley et al. 2005; Kang et al. 2013), especially the supply and regulation of water resources, timber production and pasture for extensive livestock farming, biodiversity, conservation/degradation of soils, leisure activities and several cultural values that make a substantial contribution to the economy of the mountains and adjoining areas (Körner et al. 2005; Grêt-Regamey et al. 2012; Lavorel et al. 2017; Varela et al. 2020).

Since the 1980s, most of the landscape analysis has been focussed on the landscape ecology (Forman and Godron 1986; Forman 1995; Aguilera-Benavente 2010), based on the structure formed by patches making up the landscape, their sizes, shapes, borders and spatial distribution, as well as connectivity through corridors among the formations. Some of the characteristics of the forms can be quantified using Geographical Information Systems (GIS) and a set of landscape ecology metrics or indices (Boterquilha and Ahern 2002; Turner 2005). These indices provide a numerical value (some with a defined range of variation) giving information on the evolution and changes in a specified landscape, also how to compare different landscapes, which is of great interest not only from an ecological perspective, but also for analysis, valuation and land management (Antrop 2001; Jongman 2004).

Our hypothesis is that LULC changes in the Pyrenees from the mid-20th century have constructed a more homogeneous, less fragmented landscape, with the loss of very important features of the traditional

cultural landscape. In this article, we study LULC and landscape changes in the Aísa valley in three years, (1956, 1981 and 2017), based on LULC mapping and the calculation of spatial metrics and landscape geometry indices. The objectives of the study are: (i) to analyse LULC changes between 1956 and 2017 (especially by calibrating the difference in variations in two periods: 1956–1981 and 1981–2017); within the framework of the first objective, the spatial distribution of LULC changes based on the Kappa index are described, and the transitions in LULC analysed, and (ii) to study landscape structure and fragmentation in 1956, 1981 and 2017. These issues are important within the context of current discussions on the value of biocultural landscapes, which are frequently threatened with land abandonment and subsequent revegetation, so the results obtained can provide useful information to land managers (Agnoletti 2014; van der Zanden et al. 2017; Latocha et al. 2018).

Materials and methods

Study area

The study was carried out in the headwaters and middle part of the Estarrún river, a tributary of the Aragón river in the Central Spanish Pyrenees (Fig. 1). The surface area covers 9603 ha, of which 8154 ha belong to the municipality of Aísa, and the rest to the farmland of Las Tiesas Altas, Las Tiesas Bajas and Fraginal, which form an administrative part of the municipality of Jaca. The whole study area is known as the Aísa or Estarrún valley and is representative of the changes in LULC in the Spanish Pyrenees and most of the Mediterranean mountain areas over the last century (i.e. Poyatos et al. 2003; Bejamin et al. 2005; Varga et al. 2018).

As most Spanish Pyrenean valleys, the Estarrún river forms a long valley heading south, with headwaters in the limestone and sandstone of the Inner Range, and later flowing mostly through the Eocene flysch (alternating thin layers of sandstone and marls). The latter is characterised by the dominance of stable slopes (between 20% and 40%) and gentle divides that drop down from the face of the Inner Ranges to the Upper Aragon Inner Depression. Outcrops of marls are found in the southern sector of the

study area. Altitudes in the valley range from 733 m a.s.l. along the course of the Estarrún river to the exit of the valley, up to the Aspe peak at 2645 m a.s.l.

The climate is Mediterranean mountain, with some continental characteristics and about 800–1000 mm rainfall at the valley bottom and nearby slopes, and over 1500 mm above 1700 m a.s.l. (García-Ruiz et al. 1985). Periods without rain in the sector are few and short, so there is almost no water deficit. The 0 °C isotherm is at 1650 m a.s.l. (Del Barrio et al. 1990). However, some drought periods occur below 1000 m a.s.l., especially in summer and winter (Creus 1983). Rain is concentrated in autumn and winter, with the lowest rainfall occurring in summer (Vicente-Serrano et al. 2007).

Pinus sylvestris forest dominates the shady areas, while sunny slopes have patches of primitive oaks (*Quercus gr. faginea*), alternating with sub-Mediterranean scrubland (*Buxus sempervirens*, *Genista scorpius*, *Echinospartum horridum*, *Rosa gr. canina* and *Juniperus communis*). Black pine (*Pinus uncinata*) grows in high altitudes with prolonged snow cover. Above 1600 m, subalpine and alpine pastures, and bare rock areas, scree and gravel and karstic shapes predominate (Villar and Benito 2001). The soils are brown forest, very stony and poor. Regosols, whose top horizon has frequently been removed, are abundant. The texture is loam or clay loam, lacking in basic nutrients such as potassium and phosphorus, and containing approximately 1.5% of organic matter. However, they are rich in carbonates and relatively stable (Ruiz-Flaño 1993).

The evolution of socio-economics in the study area is similar to the other Pyrenean valleys in Aragón. In 1920, there was a population of 865 (9 pers./km^2), which fell to 452 people in 1950 (4.7 pers./km^2), and 200 in 1975 (2.1 pers./km^2), while the census rose to 339 in 2022 (3.5 pers./km^2). The demographic evolution shows a sharp decline in workers from the beginning of the century, which has recovered slightly in the last few decades because of tourism activities, especially those of the Candanchú ski station, which belongs to the municipality of Aísa (Lasanta 2010). Throughout the 20th century there has also been a sharp decline in livestock, standing 440 cows and horses, and about 7000 smaller animals (sheep and goats) in 1934 according to information in the archives of the municipality of Aísa, while in 2022, there were 220 cows and 1250 sheep (data collected
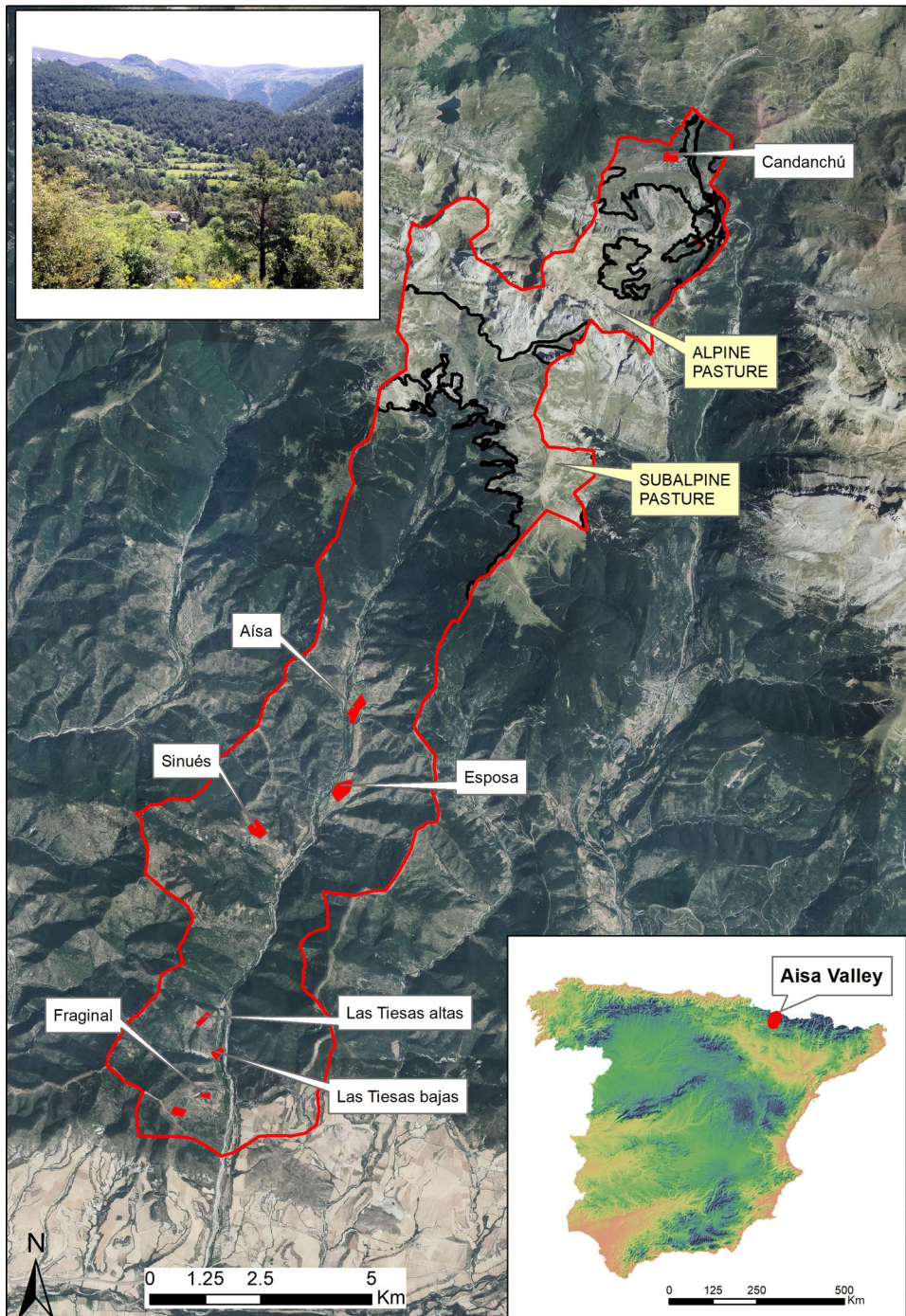
Fig. 1 Study area. Aísa Valley located in the Central Spanish Pyrenees. Location of the main municipalities. Counterlines have been added for the subalpine and alpine belts

directly from the livestock farmers by the authors). This evolution means that Large Units (LU, 1 cow or 1 mare, or 10 sheep or 10 goats) fell from 1140 to 1934 to 355 in 2022. The cultivated fields also

declined sharply as they were abandoned, falling from 2321 ha at the beginning of the century (24% of the valley surface area) to 393 ha in 2017 (4.1%) (Errea et al. 2015).

Land use and land cover mapping

The LULC has been mapped by aerial photographs, since these enable the landscape components to be interpreted (Morgan et al. 2010; Godone et al. 2014), for the years 1956, 1981 and 2017. These years were chosen as there were no photograms of the study area before 1956 or later than 2017, when mapping was carried out; 1981 is a transition year between the first and last ones. The legend contains 14 categories appropriately reflecting LULC changes: (1) bare soil and alpine pasture, (2) subalpine pasture, (3) forest, (4) forest and scrubland, (5) forest, scrubland and pasture, (6) scrubland, (7) scrubland, pasture and forest, (8) pasture, (9) pasture and scrubland, (10) pasture, scrubland and forest, (11) cultivated fields, (12) village, (13) roads, and (14) water courses. Therefore, the legend includes: 5 homogeneous categories of LULC where a single cover takes up at least 80% of the area, 6 categories combining two or more LULC with cover per class lower than 80%, with the first one occupying the largest surface area and the last one the smallest, and three LULC which have nothing to do with vegetation cover. High mountain pasture (alpine and subalpine) above 1600 m a.s.l. is differentiated from the other pastures below 1600 m a.s.l., generally at the montane belt. The former is used in the warm season (usually July to October), while the latter is pasture for the rest of the year.

Table 1 gives information on the sources used to draw up the maps. Maps for 1956 were created from photo-interpretation of rectified orthophotos from the American flight in 1956, available for downloading at https://idearagon.aragon.es/portal/. The Aísa valley is covered by 12 photos in .jpg format on a scale of 1:33,000. The 1981map uses national flights from 1980–1986 (scale 1:25,000) based on photograms downloaded from the National Geographical Institute portal. It consists of 13 photos available for downloading at http://www.ign.es, in .ecw format, at a scanned resolution of 1,100 dpi. They have been orthorectified with Erdas Imagine software, with the Leica Photogrammetric Suite (LPS) module. Processing was by stereo band pairs (6 bands) with at least 10 control points (GCP) per photo. The ETRS89 zone 30 projection system was used, with an average error of 2 m. Photo-interpretation was then made to define the 14 categories of LULC. The 1956 and 1981 maps were digitalized in ArcGIS 10.5 and geo-referenced to the ETRS89 projection system, with all the information incorporated to a vector database. The 2017 LULC map was created from the SIOSE (Information System for Land Occupation in Spain) available at www.ign.es. This is a map of land uses and land cover on a scale of 1:5,000, although presented at a scale of 1:25,000. As the map provided by the SIOSE is highly detailed, resulting in a very complex legend (large number of combinations and mosaics) difficult to interpret, it was decided to reclassify them into the 14 categories mentioned above

Superimposing the 1956, 1981 and 2017 maps enables us to know the areas where LULC has changed, either through secondary succession or because of vegetation cover regression, and the number of stages or steps they have covered in the process. This results in a very high number of combinations, making interpretation complicated. To overcome this obstacle, the number of steps was reduced and categories grouped around the first one in the legend: cultivated fields, pasture, scrubland and forest, excluding the three non-biotic categories. Figure 2 outlines possible LULC changes that could occur with this criterion. The step from one state to its immediate neighbour was valued at $+1$, if it concerned succession, and -1 for regression, with the values increased with the size of the as the jump up to maximums between -3 and $+3$. A map of the intensity of changes in LULC within the study period was created based on these parameters (Fig. 4).

Analysis of LULC transitions

Idrisi v.17 software was used to find the areas with LULC changes. A cross-tab analysis was made. This uses a transition matrix to provide the variation among categories for two years, marking the zones that maintain the same LULC and those that change to different ones. This analysis enables a coincidence index to be drawn up (Kappa index) to estimate the areas maintaining the same cover in different years, both at analysed unit scale (valley in our study) or for each category. The Kappa index (K) is a measure of concordance proposed by Cohen (1960) and

Table 1 Sources for map creation (1956, 1981 and 2017)

	1956	1981	2017
Nº photograms	12	13	1
Scale	1: 33,000	1: 25,000	1: 5,000
Resolution (m)	1	1	0.5
Source	https://idearagon.aragon.es/portal/	http://www.IGN.es	http://www.IGN.es
Height of flight	5000 m	5600 m	
Focal distance (mm)	152.04	152.47	

Fig. 2 Theoretical diagram of the number of steps to possible land uses and land cover changes, considering only cultivated fields, pasture, scrubland and forest. Steps are valued at +1, if it concerned succession, and −1 for regression, with the values increased with the size of the as the jump up to maximums between −3 and +3. Note that Step +1 from cultivate fields to pasture can last for a very short time (less than 5 years) if there is no grazing or remain for decades if the stocking rate is in accordance with grazing productivity. If it is low, it soon becomes scrubby and if it is higher than the permissible load, areas of bare soil are generated
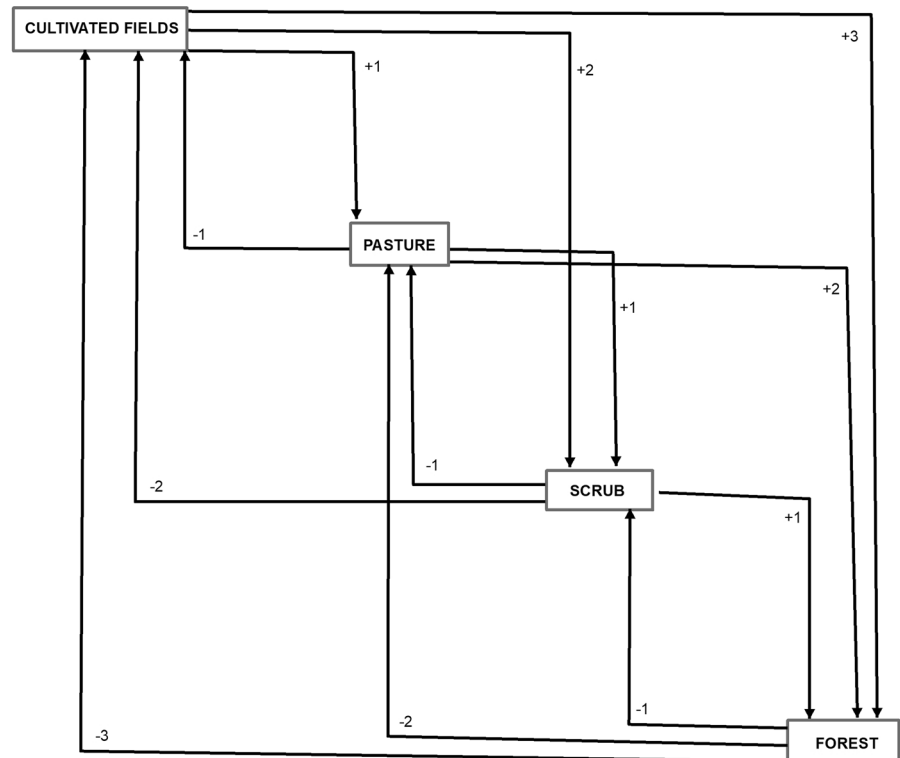
improved by Landis and Koch (1977), based on comparing the concordance observed in a set of data with that which could occur by chance. K gives values between 0 and 1 and 0 and −1. If K is 0, it means that the concordance observed coincides with that which could occur at random. Positive values show greater concordance than expected from pure chance. A value of 1 shows complete concordance; values between 0.8 and 1 a very good level of agreement; values between 0.6 and 0.8 a good level; between 0.4 and 0.6, a moderate level; between 0.2 and 0.4 a low level of agreement; and insignificant between 0 and

0.2. If K takes a negative value, there is discrepancy between both data sets.

Analysis of landscape structure and heterogeneity

The maps were transferred to vector format by ArcGIS extension V-Late 2.0 (Vector-Based Landscape Analysis Tools, Land and Tiede 2003). The program can find a set of spatial metrics and landscape ecology indices frequently used to analyse the composition and configuration of the terrain, including diversity indices and fractal dimension (Errea et al. 2007).

Several parameters have been calculated as landscape metrics in order to find the degree of fragmentation and landscape structure. Area measurements included: number of patches (NP) and mean patch size (MPS). Among the edge parameters were: total length Edge (TE), edge density (ED) and mean patch edge (MPE). The description of patch shapes was obtained from a combination of area and perimeter using the metrics: (i) Mean Shape Index (MSI), which gives values from 1 (totally circular patch) and 3 (straight line); (ii) Perimeter-area ratio (MPAR), and (iii) fractal dimension (MFRACT), which gives values between 1 (totally regular area) and 2 (totally irregular area). More information on the calculations can be found in Lovejoy (1982), Kienast (1993), Mandelbrot (1982) and Errea et al. (2007).

To characterise the heterogeneity of the terrain, the three landscape ecology indices were calculated for diversity, evenness and dominance, based on the theory of information by Shannon and Weaver (1962).

Results

LULC changes between 1956, 1981 and 2017

In 1956, the cultivated fields in the Aísa valley covered almost 840 ha, (8.7%), and then decreased to 547 ha (5.7%) in 1981 and to 490.5 ha (5.1%) in 2017 (Table 2). The main LULC change took place in the pasture located in the montane belt, which fell from 1,444.5 ha (15%) in 1956 to 301 ha (3.1%) in 1981 and 28 ha (0.3%) in 2017. A steady decrease over time is also recorded for the pasture and scrubland category, although not quite as drastic, since 63.5% of the 1956 surface area was still in use in 2017. The pasture, scrubland and forest category increased sharply during the first part of the study period (1.6% in 1956 and 5.5% in 1981), but the trend was reversed in the second part (2.3% in 2017). Scrubland as a single category covered a very small area in the three years and decreased further over the study period. However, scrubland combined with pasture and forest recorded a strong increase between 1956 and 1981 (from 8.2 ha to 624 ha) and an acute fall between 1981 and 2017 (315.7 ha). Forest, both as a single unit (homogeneous) and combined with other land cover, expanded strongly, going from 2347.5 ha (24.4%) in 1956 to 3476 ha (36.2%) in 1981 and 4834 ha (50.3%) in 2017. Subalpine and alpine pasture showed a slight downward trend, especially the

Table 2 Evolution of LULC in the Aísa valley (1956, 1981, 2017). Own source and elaboration

Uses	1956 (ha)	1956 (%)	1981 (ha)	1981 (%)	2017 (ha)	2017 (%)
1. Cultivated fields	839.7	8.7	547	5.7	490.5	5.1
2. Pasture	1444.5	15	301	3.1	28	0.3
3. Pasture and scrubland	1459.5	15.2	1086.3	11.3	926.2	9.6
4. Pasture, scrubland and forest	156.3	1.6	532	5.5	218	2.3
5. Scrubland	113.7	1.2	48.3	0.5	39.5	0.4
6. Scrubland, pasture and forest	8.2	0.1	624	6.5	308.3	3.2
7. Forest, scrubland and pasture	1301	13.5	1934	20.1	2312	24.1
8. Forest and scrubland	556.5	5.8	549	5.7	1145	11.9
9. Forest	490	5.1	993	10.3	1377	14.3
10. Subalpine pasture	1532.8	16	1390	14.5	1188	12.4
11. Bare soil and alpine pasture	1573.3	16.4	1443	15	1440	15
12. Village	16.8	0.2	34	0.35	40.2	0.4
13. Roads	13.2	0.1	16	0.17	12.3	0.1
14. Water courses	97.5	1	105.4	1.1	78	0.8
Total	9603		9603		9603	

subalpine, which lost 22.5% of its area between 1956 and 2017 (from 1532.8 ha to 1188 ha). The other three, non-biotic categories changed slightly. The most significant is the increase in the village category (16.8 ha in 1956 and 40.2 ha in 2017).

Spatial LULC changes

Figure 3 enables the spatial distribution of LULC to be compared for 1956, 1981 and 2017. The most noticeable at first are the great changes in the montane belt, while they are less severe at subalpine and alpine belts. The advance of the forest, scrubland and pasture category (purple) is clearly seen from the south sector (south on the map) to the edge of the above tree line level. In 1956, this category covered large patches, especially on both slopes of the Estarrún river above the village of Aísa. There was another large patch in the south part of the valley, close to the village of Fraginal. In 1981 and especially in 2017,

all the patches in the category had spread considerably from the original village. In 2017 the montane belt above the village of Aísa is totally covered by forest, either as a single category or combined with other types of cover, with the exception of some specific areas in the valley bottom occupied by cultivated fields.

The forest advanced mainly to the detriment of pastures, although a transition stage is seen in 1981. In 1956, the pasture and scrubland category covered wide sections in the lower and mid stretches of the valley; in 1981, the patches are less widespread and partially substituted by the scrubland, pasture and forest category; in 2017, some of the pasture and scrubland patches had disappeared completely, with forest and scrubland or forest categories taking their place.

In the western sector of the valley, the most outstanding change is the subalpine pasture being replaced by the pasture and scrubland category next to the village of Candanchú. On the other hand, the
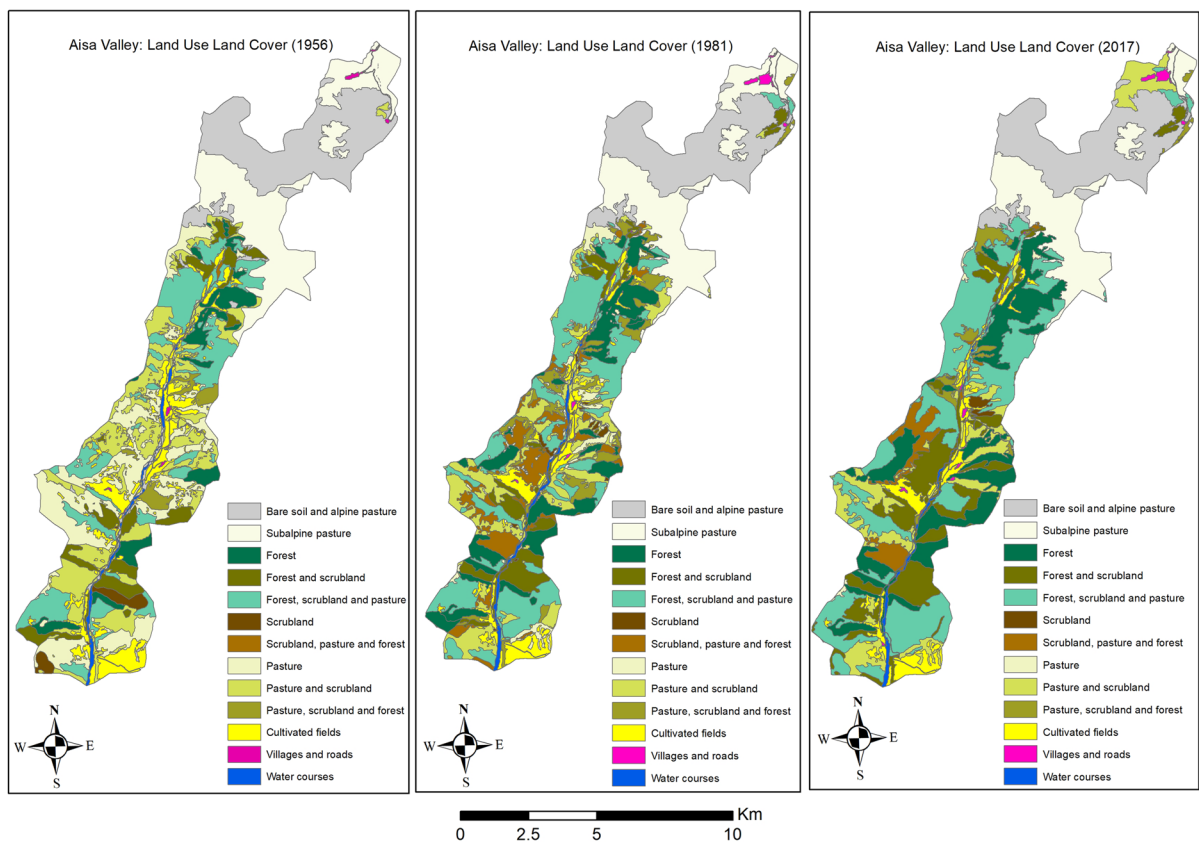
Fig. 3 Land use and land cover change in the Aísa Valley in 1956, 1981 and 2017

cultivated fields near the villages are maintained for the 3 years, also in flat areas and gentle slopes. The mid-slopes that were formerly cultivated, especially the sunny hillsides, show the greatest changes, going from cultivated fields to shapes dominated by scrubland and forest.

Table 3 includes the Kappa index values. The most notable changes took place in the first stage (K = 0.74 between 1956 and 1981) rather than the second stage (K = 0.86). There are 4 categories with a very good coincidence index (in green in Table 3) for the three

years; forest, subalpine pasture, bare soil and alpine pasture, and village. However, categories scrubland and pasture located in the montane belt have transitioned greatly (coloured salmon in Table 3) with insignificant values of K. Combined forest categories have between low and moderate coincidence values throughout the study period, recording larger changes in the first stage than the second, in which values of K include those classified as very good. Almost 47% of the cultivated fields changed between the first and last years, displaying a K index of K = 0.57, with the

Table 3 Kappa index for the overall valley and by LULCcategories over the analysed time periods

	1956/1981	1981/2017	1956/2017
Cultivated fields	0.63	0.89	0.57
Pasture	*0.11*	*0.09*	*0.01*
Pasture and scrubland	0.07	0.53	0.03
Pasture, scrubland and forest	*0.10*	*0.18*	*-0.00*
Scrubland	*0.00*	*0.04*	*-0.00*
Scrubland, pasture and forest	*-0.02*	*0.20*	*-0.00*
Forest, scrubland and pasture	0.72	0.87	0.70
Forest and scrubland	0.48	0.95	0.39
Forest	*0.92*	*1.00*	*0.97*
Subalpine pasture	*0.89*	*0.85*	*0.76*
Bare soil and alpine pasture	*0.90*	*1.00*	*0.90*
Village	0.940	1.00	1.00
Roads	0.747	0.72	0.49
Water courses	0.94	0.73	0.77
Overall Kappa	**0.74**	**0.86**	**0.71**

Very good coincidence index is shown in green in Table 3, and greatly transition in salmon

greatest changes recorded between 1956 and 1981 (K = 0.63). A very surprising result is the high rate of change in water courses, especially between 1981 and 2017 (K = 0.73), resulting in islets left by the path of the river being gradually colonised by riverbank vegetation.

LULC transitions

Table 1 Supplementary material shows the transitions in LULC between 1956 and 1981. LULC categories which underwent moderate changes are observed in the period, as subalpine pasture, the combination of bare soil and alpine pasture and areas in which forest is the main land cover. On the contrary, categories linked to pastures in the montane belt record very large changes. These categories evolve to LULC one or more levels above plant succession. Scrubland cover also underwent acute change and practically disappeared. Cultivated fields had an intermediate transition between the pasture, scrubland and forest category.

Table 2 Supplementary material gives information on LULC transitions between 1981 and 2017. Broadly speaking, it shows that the alpine pastures, bare soil and pasture, and shapes where forest is the dominant cover, remain stable, with less than 15% of transitions in all cases. On the other hand, pasture formations and scrubland change, giving rise to more evolved communities: pastures mostly change to categories with dominant scrubland, and scrubland to forest, either as a single cover or combined with others. The cultivated fields in this stage are shown to be more stable than in the previous one, remaining at 89.3%.

Table 3 Supplementary material includes transitions from 1956 to 2017. Since the period of analysis is longer, when adding the two periods analysed previously, the changes are more widespread. It is logical that the forest category displays the most stable behaviour. Combinations of forest with other covers are also relatively stable, although they undergo some change. Subalpine pasture lost surface area to pasture and scrubland, and forest shapes, although 76.5% has stayed in the same category. The combination of bare soil and alpine pasture is also relatively dynamic, with 7.5% evolving to scrubland formations, with at least 3.2% reaching the final forest stage. Pastures in the montane belt as a single category or mixed with

other cover, display the lowest stability and change to more complex formations Another significant fact is that scrubland, which was sparse in 1956, had disappeared in 2017, changing to forest with other covers.

Figure 4 gives a synthesis of the transitions during the study period. Figure 4A shows that between 1956 and 1981 there were large changes in LULC, especially in the middle and lower sections of the valley. Higher areas recorded fewer transitions. The main change in this stage was from pasture to scrubland, followed by scrubland to forest, and pasture to forest. A very localized view is of the upper reaches of the Estarrún river and next to the riverbed, where there are areas that have changed from farmland to forest. Figure 4B highlights the fact that the changes affected a smaller area in 1981–2017 than in the previous period (1956–1981). The main transition was from scrubland to forest, followed by pasture to scrubland, which occurred across all high areas, with the largest patch next to Candanchú. The third significant transition is from pasture to forest. Figure 4C shows the changes from 1956 to 2017, i.e. over a period of 6 decades, meaning that a large part of the area has undergone change. Three transitions stand out: from pasture to forest, from scrubland to forest, and from pasture to scrubland. At local level, a change from cultivated fields to forest is also observed, frequently forming very small patches on the valley floor. Lastly, the transition of cultivated fields to pasture must be noted, coinciding with the latest abandoned fields.

Dynamic of the landscape structure

Table 4 gives information on the structure and diversity of the landscape in the three years under study. It can be observed that the number of patches was stable in the first period (slightly increment) and then fell between 1981 and 2017. It is logical that the MPS links to NP, thus in 2017, with 38% fewer NP than in 1956, a larger MPS was recorded (22.3 ha in 1956 and 35.3 ha in 2017). The fewer number of patches implies that the edge lengths reduced while, at the same time, the edge density decreased; on the other hand, the highest average length of the patches is found in 2017, coinciding with the smallest NP and largest MPS.

The Shannon diversity index and the evenness index were stable during the first period and decrease between 1981 and 2017, whereas the dominance
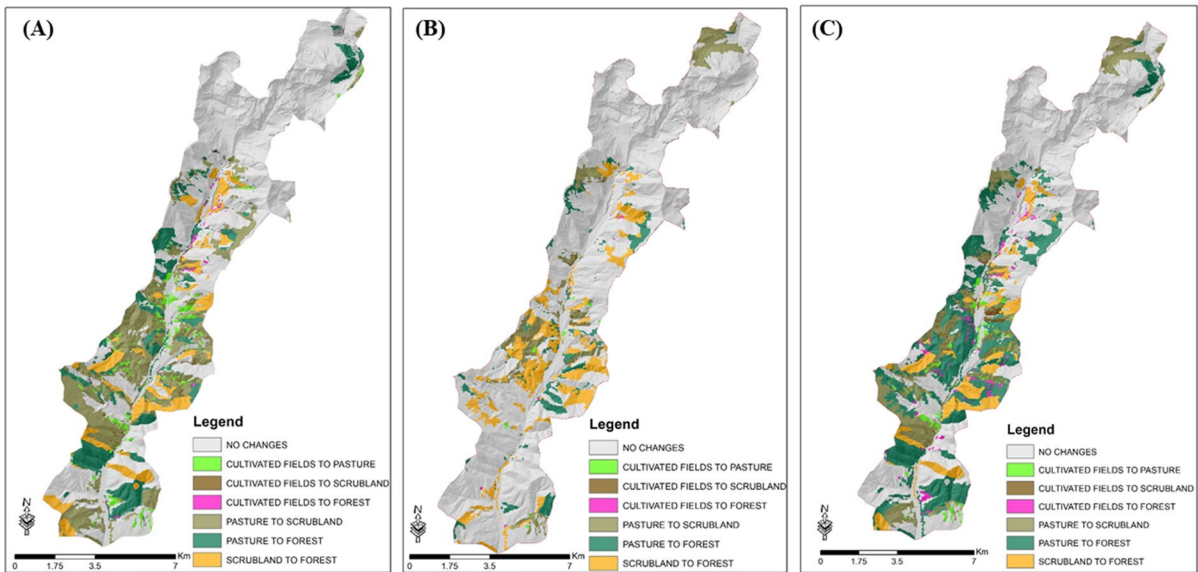
Fig. 4 Spatial transitions in LULC in the Aísa Valley (1956–2017). **A** transitions between 1956 and 1981; **B** ransitions between 1981 and 2017; **C** transitions between 1956 and 2017

Table 4 Structure and diversity of the landscape in the Aísa valley (1956, 1981, 2017)

		1956	1981	2017
Area	Total surface area (ha)	9603.3	9603.3	9603.3
	Number of patches (NP)	436	476	272
	Average patch size (ha) (MPS)	22	20.2	35.3
Borders	Total length of edges (km) (TE)	1128.1	1210.9	986.6
	Edge density (m/ha) (ED)	117.1	125.8	102.7
	Mean patch edge (m) (MPE)	2587.3	2543.9	3627.2
Diversity	Shannon index	2.165	2.261	2.117
	Evenness index	0.820	0.857	0.802
	Dominance index	0.474	0.378	0.522
Shapes	Mean shape index (MSI)	1.984	2.037	2.235
	Perimeter-area ratio (MPAR)	0.05	0.046	0.226
	Fractal dimension (MFRACT)	1.366	1.366	1.402

index increases in the last period. However, it is not a linear trend, since the highest diversity and lowest dominance is reached in 1981. The results for the landscape shapes show minimal changes, although the MSI and MPAR increase slightly. Nevertheless,

the value of MFRACT is the same in 1956 and 1981 (1.366), rising to 1.402 in 2017. Only a few decades after ceasing traditional activities, the Aísa valley landscape was characterised by a core of forest and succession scrubland, with very few large patches and more circular that elongated shape (MSI values of 2.235 in 2017, and 1.984 in 1956), while hardly any open patches of pasture or cultivated fields are seen if the valley bottom is excluded (Fig. 5C).

Discussion

Land uses and land cover changes

From the beginning of the 20th century, the Pyrenees, as most of the Mediterranean mountains, witnessed the gradual reduction in anthropic pressure on the territory (Taillefumier and Piégay 2003; Kizos and Koulouri 2006; García-Ruiz et al. 2015). The cultivated fields no longer fulfilled their basic function (feeding the population) as emigration to the cities grew and the exchange of products between the mountains and lowlands became more fluid (Lasanta 1988; Molinillo et al. 1997; MacDonald et al. 2000; Sancho-Reinoso 2013). At the same time, the transhumance system, which had enabled large flocks of sheep for centuries,

Fig. 5 A Rapid advance of scrubland and open forest (*P. uncinata* and *P. sylvestris* in subalpine and alpine pastures due to reduced livestock pressure and higher temperatures; **B** High undergrowth and forest density in the montane belt; **C** Forest and scrubland expansion in the Aísa Valley, with a small patch of pasture in the valley bottom

went into decline and disappeared in the Aísa valley in the mid-20th century, without the slight increase in cattle being able to compensate for the huge loss in sheep (Calvo Palacios 1970; Ruiz-Flaño 1993). These conditions meant that farming tended to concentrate in very specific areas: the valley bottom of the Estarrún river and around the villages, cultivated for meadows, and the most accessible subalpine pasture used in the warm season. At the same time, most of the area underwent an obvious process of concentration of production and even total land abandonment (Molinillo et al. 1997; Lasanta et al. 2021). In that sense, several noteworthy facts about the Aísa valley have emerged in the last century: a fall in the population (almost 64%), cultivated fields (80%), and livestock numbers (69.8%), especially sheep.

Marginalised production, in particular the abandonment of cultivated fields and pastures, promoted large LULC changes. Thus, forest as a single formation or combined with other land cover, more than doubled in surface area, going from 2347.5 ha in 1956 to 4834 ha in 2017. On the other hand, the pastures in the montane belt lost 1989 ha (63% of their area) and cultivated fields 349.2 ha (42%), between the same two years. The changes above the tree line were less obvious, although pasture was lost to scrubland. The dynamics of LULC in the Aísa valley matches that observed in other Mediterranean mountains, where the forest has advanced greatly to the detriment of cultivated fields and pastures (Agnoletti 2007; Facucci et al. 2007; Sitzia et al. 2010). It is possible to re-establish forest in abandoned land in regions where the potential for vegetation is forest (Zerbe 1998). In this respect, Bracchetti et al. (2012) found that, in the

central Appenines (Italy), it took 23 years to reach the forest stage after land abandonment, without going through a stage of strongly dominant scrubland. Lasanta et al. (2020a, b) observed that the terraced slopes in the Pyrenean valley of Bestué (Huesca, Spain) still grew cereals in the 1970s, whereas they were covered with dense forest at the beginning of the 21st century. Abandonment of fields and lack of pasture made rapid secondary succession very possible, leading to a landscape of mature forest within 5 decades. The authors base their arguments for the fast revegetation process on three explanations: (i) the high altitude of the terraces (between 1000 and 1500 m a.s.l.) allowing heavy rainfall (between 1200 and 1500 mm/yr) and avoiding water stress; (ii) good soil quality, due to its depth and pasturing sheep after the land was no longer cultivated, which contributed to improving soil fertility; and (iii) the presence of trees (mainly *Q. faginea*) along the terraces which has helped rapid penetration in the flat terraces.

However, not all hillsides follow the same rate of plant succession, and there is frequently a very long stage of scrubland dominance between those of pasture and forest (Preiss et al. 1997; Roura-Pascual et al. 2005; Pueyo and Beguería 2007; Peña-Angulo et al. 2019). In the Aísa valley, Molinillo et al. (1997) found that not all stages in plant succession needed the same amount of time, and concluded that a recently abandoned cultivated field very rapidly changed to pasture and then to scrubland, whereas the change from scrubland to forest takes much longer, and is the transition that mostly limits the time of plant succession. This study found that the most important transition between 1956 and

1981 was from pasture to scrubland at the montane belt (see Fig. 4A), since there were a great number of abandoned fields in 1956 that had already started secondary succession, and were mainly pasture. Errea et al. (2015) stated that the cultivated fields in the Aísa valley covered 2321 ha at the beginning of the 20th century, of which 1501 ha had been abandoned before 1956. In the 25 years (1956–1981) other areas changed from scrubland to forest and were the two most important transitions. Thus, most of the changes recorded covered a stage in plant succession. In the second period (1981–2017), the most notable change was from scrubland to forest, followed by pasture to scrubland. A single stage in succession also covers 36 years (Fig. 4B). However, when the whole period (1956–2017) is analysed, the most important transition is observed from pasture to forest, so that 61 years seems to be enough time for some areas of the Aísa valley to have reached the final stage in plant succession. It is also true that a large part of the area has only undergone one stage (from pasture to scrubland) at a slower rate of plant succession (Fig. 4C).

A factor that can speed up or slow down secondary succession is soil fertility. Errea et al. (2015) studied this in the Aísa valley, taking the types of field into account. They found that flat fields (almost always those with the best soil) abandoned before 1956 reached the forest stage in greater proportion than those where slash-and-burn techniques were used on shallow, very poor soil. The same authors observed that management after abandonment often explains the succession rate, so that heavily grazed abandoned fields slow down scrubland and forest evolution. In addition, Vicente-Serrano et al. (2003, 2004a) found that, in the neighbouring Borau valley, topography is very important to the rate of plant succession. Thus, gentle slopes tend to have fertile soils that speed up the succession, if they are not heavily grazed, which slows it down. The slope and exposure determine sunlight, promoting succession if the plants do not suffer water stress. However, in the Leza valley (Iberian Mountain range, Spain), which has gentle slopes and moderate altitudes, climatic variability could be more important than topography in explaining post-abandonment spatial distribution of scrubland and forest succession (Peña-Angulo et al. 2019). Together with environmental factors, land management plays a decisive role, conditioning the rate of succession and distribution of areas with revegetation or regression

(Vicente-Serrano et al. 2004b; García-Ruiz and Lana-Renault 2011; Lasanta et al. 2021). In short, the strong inter-relationship between the physical conditions in the mountains and human management make it advisable to consider the influence from all variables when explaining changes in LULC following land abandonment, although some of the factors only intervene indirectly in the process under study (Vicente-Serrano et al. 2004b; Lasanta et al. 2021).

In Mediterranean mountains with less humid climatic conditions than those of the Aísa valley, it has been found that plant succession presents a slower rhythm, so that the forest phase is hardly reached (Bonet and Pausas 2004; Jiménez-Olivencia et al. 2021), which has prompted afforestation programs in order to achieve forest areas quickly (Villar-Salvador 2016).

Among the results from this study is the fact that 29% of plant cover in the territory changed between 1956 and 2017. The changes mainly took place at the montane belt, where many of the hillsides, formerly cultivated or used for grazing, are covered by scrubland and forest following abandonment (Errea et al. 2015). However, it must be pointed out that in the second period analysed, a rapid advance of scrubland and open forest was observed (especially *P. uncinata* and *P. sylvestris* (Fig. 5A) in subalpine and alpine pastures, due to reduced livestock pressure and higher temperatures (Nogués-Bravo et al. 2008; García-Ruiz et al. 2015). This dynamic can be seen throughout the Central Pyrenees (Gartzia et al. 2014; Nadal-Romero et al. 2018), in the Alps (Caviezel et al. 2017) and in the Appenines (Palombo et al. 2013). In the near future, the revegetated surface area may be more widespread at subalpine level than in the montane belt, once it has covered a large part of the open spaces, so it will help more with the density of the forest and undergrowth (already very dense in some pine forests, see Fig. 5B). Future revegetation could severely affect the reduction of water resources, as stated by Khorchani et al. (2021) in the Aísa valley, with increased fire risk (Badía et al. 2002; San-Miguel-Ayanz et al. 2013; Varga et al. 2018), a loss of pasture resources (Komac et al. 2013; Gartzia et al. 2016; Nuche et al. 2018), reduction of areas for skiing (Gilaberte-Búrdalo 2018) and less biodiversity (Newbold et al. 2015; García et al. 2019) and soil organic carbon sequestration (Nadal-Romero et al. 2018).

Pastures and scrubland showed the largest transitions. Plant succession processes were more common than regression; these took place in very specific contact sectors between the montane and subalpine slopes, where small amounts of felling and elimination of scrubland has been carried out to improve grazing quality. Plant succession, on the other hand, is a process that has affected much larger areas than regression. This is logic in a landscape that has been intensively abandoned, as it is suggested by different studies. Revegetation due to secondary succession is very common in the Mediterranean mountains as stated in several studies: Molinillo et al. (1997); Poyatos et al. (2003); Vicente-Serrano et al. (2004b); Chauchard et al. (2007); Gellrich et al. (2007); Pueyo and Beguería (2007); Tzanopoulos et al. (2007); García-Ruiz and Lana-Renault (2011); Komac et al. (2013); Cervera et al. (2019); Lasanta et al. (2021), among others.

Landscape changes

Plant succession process is highly complex, since it is determined by natural and human factors (Veysset et al. 2005; Van Vliet et al. 2015). This leads to the landscape following different patterns, either tending to homogenization or else to a more diverse and more complex landscape (Lasanta-Martínez et al. 2005; Rey-Benayas et al. 2007; Verburg et al. 2007). Both patterns have occurred over time in the Aísa valley; in the first stage (1956–1981) there is increased heterogeneity (higher diversity and evenness indices in 1981 than 1956) and fragmentation (more patches that are smaller, less even and of various types), while the second stage had increased homogeneity (higher dominance values) and defragmentation (fewer patches, larger than the above and more elongated shapes). These results show that abandonment of the land and customary management methods at first give rise to increased landscape diversity, as features of the traditional landscape live side-by-side with areas undergoing transformation, covered by grasses, scrubland or forest, depending on the stage reached in plant succession. However, the passing of time leads to a stage in which the plants eliminate all traces of the traditional landscape, and forests become the core formation, as others have confirmed: Vicente-Serrano et al. (2000) in the Borau valley (Central Pyrenees), Varga et al. (2018) in the eastern Pyrenees, Lavorel

et al. (2017) in the Swiss and Austrian Alps, and Taillefumier and Piégay (2003) in the French Pre-Alps. The four studies emphasise that land abandonment leads to a simplified landscape and the loss of the traditional mosaic landscape, where several patches with different uses and plant cover live side-by-side and give rise to a cultural landscape contrasting with the current ones, which have widespread scrubland and forest succession.

The loss of heterogeneity and the simplification of the landscape is taking place in all Mediterranean mountains that record land abandonment, since the traditional landscapes need a great deal of work to maintain the mosaic structure and open habitats, work which no longer takes place with land abandonment and the disappearance of maintenance (hedges, paths, terraces, ditches, etc.) and traditional management tasks that were proven beyond measure to be effective at ensuring diversity and sustainability (Meeus et al. 1990; Vila Subirós et al. 2009; Sitzia et al. 2010; Heredia et al. 2013; Lasanta et al. 2020a, b).

Homogenization and defragmentation of the landscape leads to the disappearance of cultural landscapes, which result from centuries of integration between natural processes and land management (Farina 2000; Antrop 2005; Palang et al. 2005; Agnoletti 2014: García-Ruiz and Lasanta 2018). The loss of cultural landscapes is thought to be a significant problem for ecosystem services to the public, since they make a substantial contribution to the socioeconomy of the lowlands, in addition to the mountains (Agnoletti 2007; Grêt-Regamey et al. 2012; Bernués et al. 2014; Kozak et al. 2017; Lavorel et al. 2017; Schmitz et al. 2017; Cervera et al. 2019; Faccioni et al. 2019). Water and grazing resources, carbon sequestration, preservation of biodiversity, fire control and socio-cultural services are among the affected ecosystem services. Therefore, certain management guidelines are oriented toward maintaining or restoring open habitats and mosaic landscapes in mountain areas, with special emphasis on preserving pastures and abandoned agricultural slopes (Pinto-Correia et al. 2006; Bracchetti et al. 2012; Antrop 2014; Schmitz et al. 2017; González Díaz et al. 2019).

However, current socio-economic trends mean that sustaining or re-establishing landscapes is often impractical: obtaining financial resources is difficult and fairly unprofitable, as the over-compartmentalization of spaces makes land management complex and

limits start-ups of programmes to reintegrate abandoned land into the production system (Lavorel et al. 2017). In addition, some scientists and the public think nature should follow its own course *(re-wilding)* so that the landscape gradually becomes more natural, which would lead to increased regulation ecosystem services (Schnitzler 2014; Pereira and Navarro 2015). Moreover, in some regions of the Mediterranean mountains, plant succession is very rapid and reaches the forest stage within 5–6 decades (Bracchetti et al. 2012; (Lasanta et al. 2020a, b; Ameztegui et al. 2021). It is evident that traditional practices have disappeared irreversibly and new management models are required that include heritage knowledge and values and preserve natural capital (Antrop 2014). In this respect, a significant result from our study is that diversity and fragmentation expand during the first few decades following land abandonment, and so land managers must take action at this stage if they want to improve the landscape structure and increase biodiversity. In relation to the above, moderate intervention has taken place (clearing scrubland and prescribed burning combined with extensive livestock farming) in several mountain landscapes with very positive results for the environment, socioeconomy and the landscape; these actions also enable ecosystem services for regulation, supply, support and culture to be recovered (Conti and Fagarazzi 2005; Fernandes et al. 2013; Lasanta 2019; Múgica et al. 2021).

In areas with a long history of human management, such as the Mediterranean mountains, it should be asked whether abandoning farming activities is the best option for sustainability, biodiversity and the supply of ecosystem services, or is proactive management of the terrain better, such as light intervention in selected areas e.g. the most accessible abandoned land that is sufficiently fertile and on gentle slopes. Some studies conclude that, in cultural landscapes, human intervention increases biodiversity and complexity in the landscape (Conti and Fagarazzi 2005; Bauer et al. 2009; Agnoletti 2014; García-Ruiz et al. 2020), while rewilding leads to a uniform landscape, negatively affecting biodiversity, production and aesthetics (MacDonald et al. 2000; Otero et al. 2015).

Conclusions

The objective of this study was to analyse LULC and landscape changes in a valley of the Spanish Pyrenees between 1956 and 2017, using aerial photographs from the past and metrics and indices of landscape ecology. It was observed that changes in LULC affected 29% of the area, more at the montane belt than at subalpine and alpine belt, with forest doubling in size in just 6 decades. We also found very large changes in the structure and diversity of the landscape, both in the first and second study periods, caused by depopulation and later abandonment of traditional agricultural and livestock farming. This result confirms the general trend of the landscape change seen in most of the Mediterranean mountains in Europe.

A notable result is that in the first few decades following abandonment, fragmentation and heterogeneity in the landscape increase, but it later becomes very uniform, dominated by forest succession forming the core of the landscape. This suggests that any action aimed at improving biodiversity and supply of ecosystem services must be carried out during the first stages of plant succession, preferably before reaching the forest stage.

Future scenarios forecast that revegetation will continue, and that the few open spaces still existing on the montane belt will disappear and forests become denser, while scrubland and conifers will cover increasing amounts of land at subalpine belt (without taking natural disturbances into account). The landscape will be more natural but will lose ecosystem services. Future landscape planning and policies should work together to achieve mosaic landscapes which provide good opportunities for several uses and functions, by combining areas of production (extensive livestock farming, tourism, leisure) with others aimed at supplying ecosystem services.

Declarations

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

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