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Managing abandoned Mediterranean mountain landscapes: The effects of donkey grazing on biomass control and floral diversity in pastures

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ABSTRACT

Traditional Mediterranean Mountain landscapes in Spain have suffered dramatic environmental and social changes over the last seven decades. The loss of these landscapes has had consequences for biodiversity, soil erosion, landscape quality and ecosystem services as croplands and pastures were mainly converted into forests and scrublands. Many animal breeds present in traditional land uses such as the Catalan donkey (*Equus asinus* var. *catalana*), are also at risk of extinction, but can provide environmental services while recovering traditional landscapes. In Puy de Cinca, a village in mountainous northeast Spain, we studied how grazing by Catalan donkeys reduces pasture biomass and the effects on plant diversity in pastures. We used Sentinel-2 satellite imagery to calculate the Normalized Difference Vegetation Index (NDVI), a biomass sensitive spectral index, throughout the grazing period to monitor pasture biomass and compared it to pastures without grazing. We also calculated several plant diversity indicators in pastures with and without grazing donkeys. Furthermore, we studied land use changes over the last seven decades using old (1956) and current (2018) aerial images, with forest, agricultural lands, and trails interconnecting the village being mapped to understand landscape changes. The results indicated a great increase in the forested area (348.3 ± 17.0 ha). Meanwhile, a severe decrease in cropland area (73 %) and trail length (62.5 %) was also observed. Concerning the effect of donkey grazing, biomass was lower in pastures with grazing donkeys, with NDVI values decreasing once donkeys started grazing. Nevertheless, plant diversity was higher in pastures with grazing donkeys than in abandoned pastures. This study demonstrated the capacity of low-to-moderate-intensity donkey grazing to improve plant diversity and reduce biomass in pastures. Furthermore, the study of land use changes allowed an understanding of landscape dynamics, which can help address the social and environmental recovery of the village.

1. Introduction

Mountainous areas across Spain have suffered dramatic social and environmental changes over the last few generations. The changes that the country experienced from the mid-nineteenth to the twentieth century have contributed to population growth and therefore an increase in demand for agricultural products, which has required more land to be put under cultivation (Collantes and Pinilla, 2012; Garrabou i Segura, 1985). Along with agricultural expansion, a considerable increase in the extraction of forest resources during industrialization and urbanization contributed to a generalized deforestation (Iriarte-Goñi, 2008). Since the mid-twentieth century, the mechanization and intensification of farming in the most suitable lowlands made mountain farming economically unviable, and resulted in a generalized abandonment of the hillslopes (García-Ruiz et al., 1996). In the case of the Spanish Pyrenees and the Iberian Range, more than 90 % of the originally cultivated land has been abandoned (Ruiz-Flaño, 1993). Moreover, in some mountain areas in Spain, dams were built and the most productive areas ended under water (García-Ruiz, 1977). Many villages also ended under water, and others were abandoned by the locals who moved to larger towns or metropolitan areas because they could not earn their livelihoods in the countryside.

These changes have degraded many traditional mountain landscapes, which were territories shaped by the social, cultural and physical realities of their historical communities (Greider and Garkovich, 2010). The loss of traditional landscapes has had consequences for biodiversity,

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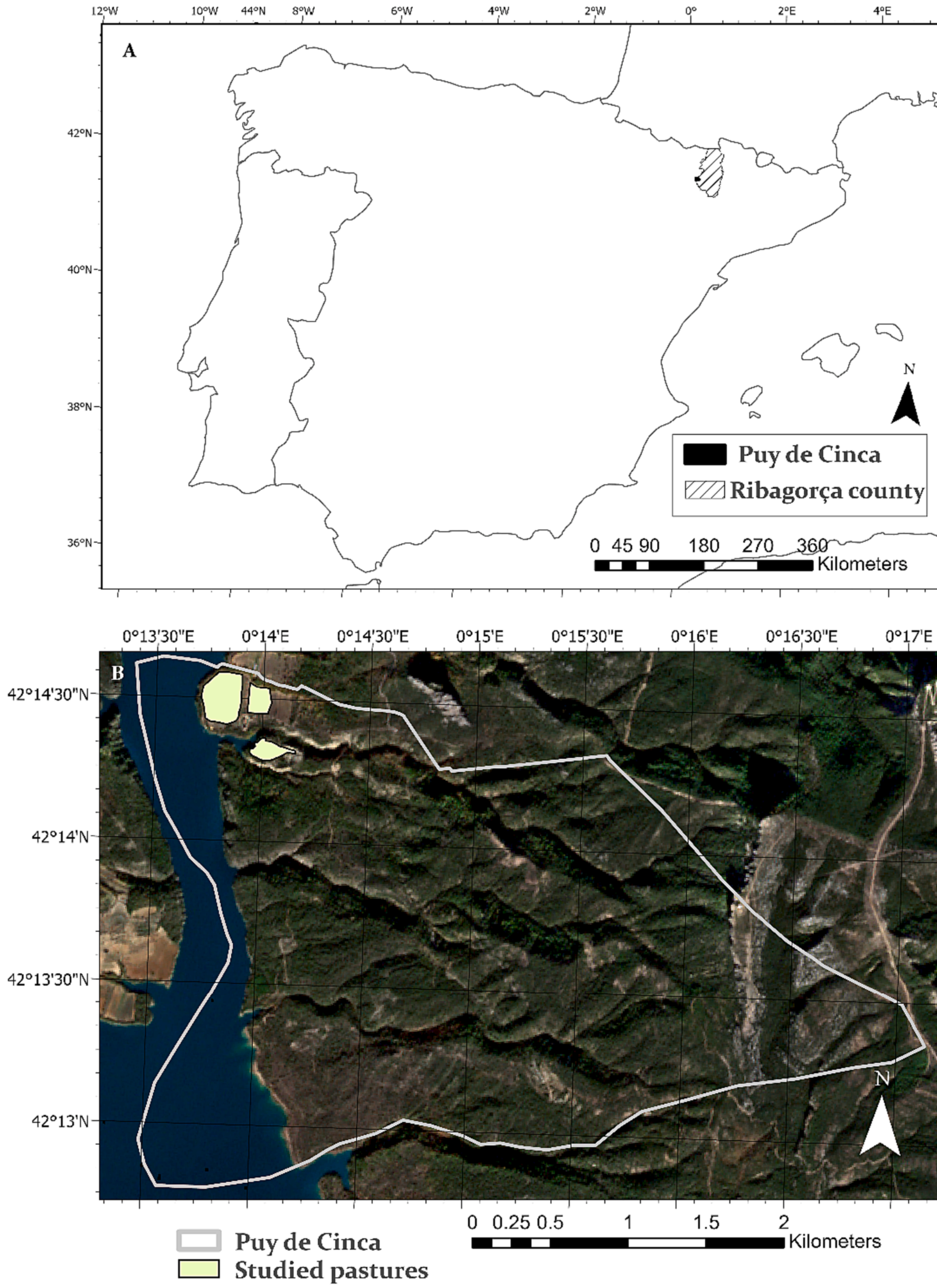

Fig. 1. The location of Puy de Cinca and Ribagorça county in northeast Spain is shown in A, while B shows the extent of Puy de Cinca and the location of the studied pastures overlies a false color Sentinel-2 image captured on the 21st of November 2020.

soil erosion, landscape quality and ecosystem services (Geri et al., 2010; Navarro and Pereira, 2015). Croplands and pastures were mainly converted into scrublands and forests which, alongside reforestation and afforestation based fundamentally on conifers (especially *Pinus* spp.) since the 1950s (Gomez Mendoza and Mata Olmo, 1992), has resulted in fuel accumulations that have increased the fire risk in most of these unstructured landscapes (Duguy et al., 2007; Jiménez-Olivencia et al., 2021). These traditional mountain landscapes are particularly vulnerable to global and climate change (Guiot and Cramer, 2016; Zamora et al., 2007), however, sustainability scenarios to mitigate and adapt to climate change imply conservation and recovery of these landscapes (Malek et al., 2018).

In contrast with other areas of the world, in Europe there is evidence of declines in the previously high biological value of long established agroecosystems (Donald et al., 2001) following agricultural intensification and abandonment of marginal and mountainous lands. Within the Mediterranean Basin, traditional land use systems had a high biological diversity, which probably never existed in pristine oak woodlands but did exist in systems that were moderately modified such as traditional agro-silvo-pastoral systems (Blondel and Aronson, 1995). For instance, pastures account for 47 % of plant species of the total flora of the Aragonese Pyrenees in Spain, but pasture barely occupies 10 % of the region's area (García and Gómez, 2007). At the same time, many animal breeds present in traditional Mediterranean land uses such as *Equus asinus* var. *catalana*, known as the Catalan donkey, are also at risk of extinction (Bartolomé et al., 2020; Gutierrez et al., 2005; Jordana i Vidal and Folch Lopez, 1998). Of all livestock, donkeys have experienced the greatest effects of rural depopulation and agricultural industrialization, and most European donkey breeds are disappearing (Kugler et al., 2007). At the beginning of the twentieth century, the number of

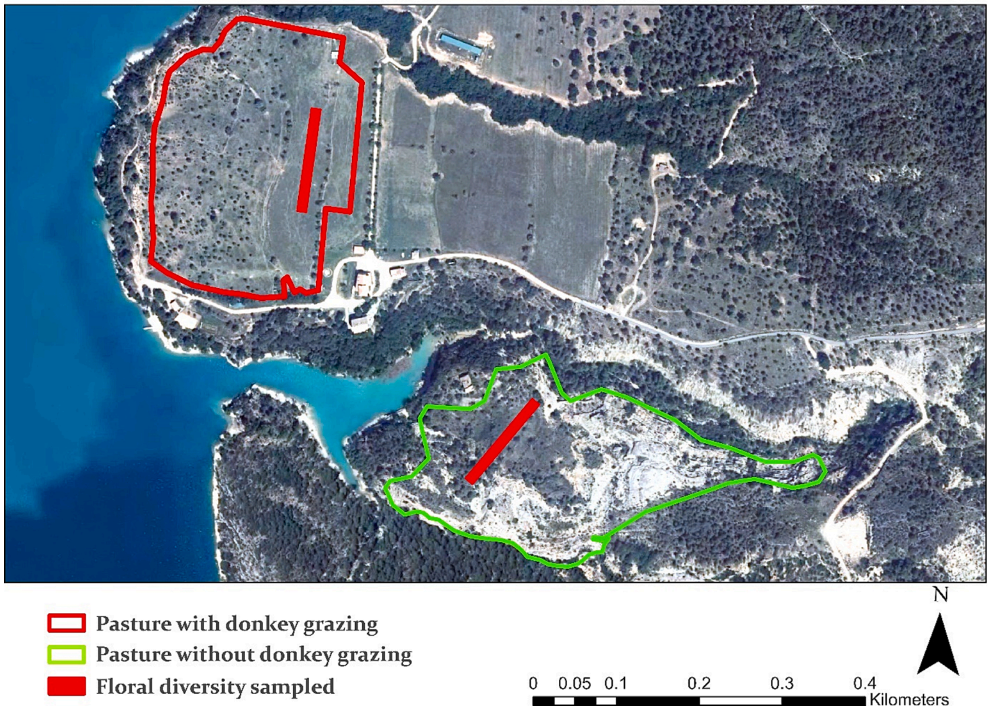

Fig. 2. Location of floral diversity sampling in a pasture with donkey grazing and an abandoned pasture, the transects followed during the sampling of floral diversity is indicated. The background image is an aerial orthophoto composition generated by the Spanish National Plan of Aerial Orthophotography in 2018.

Catalan donkeys was around 50,000, but by the 1990s only 100 Catalan donkeys were left (Jordana, 2010). Some effort has been made since then to recover the declining population of this landrace and currently the total population of Catalan donkeys is around 1,000. Therefore, providing donkeys with an environmental service role and strengthening their function in recovering traditional mountain landscapes could help recover the donkey's declining population.

Allowing large herbivores to roam freely, within the carrying capacity of an area, can contribute, to some extent, towards biodiversity conservation, and it is sustainable economically (Schwabe et al., 2013; Timmermann et al., 2015) because forage supply is generally not needed. Moreover, it is sustainable environmentally as this practice limits the input of additional nutrients into the habitat. Some authors have also observed an increase in floral diversity in pastures supporting large herbivores (Köhler et al., 2016), while others argue that grazing might have negative effects such as soil erosion and biodiversity loss in some cases (Papanastasis et al., 2002), especially due to overgrazing on poor soils. Besides biodiversity, large herbivores, such as donkeys, feed on some forest species and can play a role in fire prevention by controlling the forest understory (Bartolomé et al., 2020). Donkeys have been used successfully to control some flammable grasses in the Mediterranean scrub (Gulías et al., 2016). In other mountainous areas in Spain, different livestock species have also been used in forest lands to prevent fire risk and to restore pastures (Álvarez-Martínez et al., 2016; Casasús et al., 2004). In this sense, grazing can contribute to managing forest understory vegetation to prevent fire, and thus restore pastures, increase biodiversity (Verdú et al., 2000), and provide ecosystem services such as the activation of rural economies (Gutierrez-Peña et al., 2016).

The study we present aims to assess the effects of Catalan donkey grazing on biomass control and floral diversity in pastures for an improved environmental management of an abandoned mountain landscape. We focus on a mountainous area (Puy de Cinca, Aragon, northeast Spain), which has a deeply degraded traditional landscape due to the abandonment of settlements in the mid-twentieth century after the construction of a dam during Francoist Spain. However, since the end of the 1990s the local farmers union has addressed the rehabilitation of some settlements and promoted the reestablishment of local animal landraces. Currently, there is a significant Catalan donkey population used for transportation by some locals, as well as to reduce forest understory, recover pastures and the landrace itself. In this study, we have used an integrative approach by combining the study of traditional landscape changes, plant diversity assessment, and remote sensing that, to our knowledge, has not yet been used for monitoring donkey grazing effects on pasture biomass. With this aim we have structured the study around three research questions. First, how much has the traditional landscape changed since the mid twentieth century (1956–2018) in Puy de Cinca? Second, does the grazing of Catalan donkeys reduce pasture biomass and phytovolume? Third, is floral diversity in pastures with grazing donkeys greater than in abandoned pastures?

2. Materials and methods

2.1. Study area

In Aragonese, the local language, Puy de Cinca (known as Pui de Cinca in Aragonese) means an elevated territory above the Cinca river. After the construction of a dam in 1960s, the village was abandoned either due to the existence of certain pressures or a strategy to encourage the affected population to favor voluntary expropriation (Buil, 1993). Significant parts of the village were flooded because of the construction of the Grado dam on the Cinca river, and other villages that were located close to the river basin were also affected requiring inhabitants to relocate to other towns and cities. Puy de Cinca is characterized by two main settlements; on the one hand, the main historic village of Puy de Cinca, and on the other, a settlement of disperse traditional farmhouses called Aldea de Puy de Cinca. This municipality, as well as most of those that comprise the Aragon highlands, underwent reforestation with *Pinus* spp. after the 195 s (Grasa, 2017).

In the late 1990s Aldea de Puy de Cinca started a rehabilitation process since the owner of the land, the company managing the region's hydraulic infrastructure (Confederacion Hidrologica del Ebro) agreed to

Fig. 3. Sampling 1 m^2 to determine floral diversity.

a stewardship with the Union of Farmers of Aragon (Union de Agricultores y Ganaderos de Aragon). Several buildings were restored and 20 ha of olive trees, 2 ha of vineyards and some pastures were rehabilitated. Moreover, the Union of Farmers of Aragon also promoted the conservation of animal landraces local to the Pyrenees such as the Catalan Donkey, the Churra Tensina sheep or the Pyrenean goat (Azon-Pardo, 1998). Nowadays, the village has four inhabitants who run an inn where environmental courses are held. The village occupies about 1,000 ha, of which about 90 ha area are now inundated (Fig. 1).

In the study, we assessed land use changes across the entirety of Puy de Cinca (Ribagorça county, northeast Spain), an area located in the transition between the Mediterranean climate and mountainous temperate climate typical of the Pyrenees (Fig. 1). In regard to grazing, we studied three pastures: a donkey-grazed pasture (from June to September 2020), a pasture that was recovered in previous years but was not grazed during the studied season, and an abandoned pasture that had not been completely restored and had undergone minimal grazing in recent times. During the study season, the latter abandoned was not grazed. The two recovered pastures had been recovered in the previous six years. The locations of the pastures are shown in Fig. 1, and detailed information of each pasture and the methodology implemented is described in the subsequent sections.

2.2. Floral diversity

The floral diversity was studied in two pastures of similar sizes encompassing 6.5 ha of the pastured area, and 5 ha of the abandoned area (Fig. 2). The pasture grazed by donkeys (42°14′32.43″ N, 0°13′53.31″ E at 465 m.a.m.s.l.) during the study season (June to September 2020) carried eight Catalan donkeys (*Equus asinus* var. *catalana)* on a permanent basis (aged between two and 12 years), which can be considered a low-to-moderate grazing intensity with approximately 1.2 animals per ha, since low, moderate and high grazing intensities correspond to 0.5, 1.5, and 2.5 animal unit/ha, respectively (Török et al., 2016). This pastured area had been visited by donkeys since 2014 and therefore its abandonment was considered reversed. The donkeys started to graze the pasture in June 2020 so, the floral diversity was assessed throughout the seasons until spring (2021) because the results of floral diversity depend on the flowering stages. A GPS collar (Digitanimal, Madrid, Spain), which is specially designed for animals, was hung around the neck of one adult donkey according to the animal welfare regulations (11/2003 Spanish law on animal welfare). The GPS collar was checked regularly, as well as the general well-being of all donkeys following the regulations for Equidae in Spain (804/2011 Spanish Royal Decree). GPS devices can help monitor the welfare of animals and behavioral parameters (Herlin et al., 2021). The GPS collar determined the grazing patterns and locations of the selected donkey to enable better management of the herd, but the data were not included in the study because most donkeys were not geolocated. From the observation of GPS points and by site managers, we can argue that grazing was distributed relatively evenly throughout the pasture. The second pasture was abandoned in the 1960 s (42°14′22.86″ N, 0°14′02.94″ E, at 472 m.a.m.s.l.), and has a rugged terrain that makes its restoration more difficult. It was sparsely grazed by free-roaming donkeys nearly a decade ago, so the vegetation has experienced minimal alteration. During the study season no donkey grazing was permitted in this area in order to avoid effects on the plant community. In each pasture, either grazed and not grazed, 1 m^2 squares were placed every 10 m in a 100 m transect, totaling 10 squares, and covering a significant part of the pastures (Fig. 2). Samples were taken in each of the squares throughout the transect (Fig. 3). All species were collected and classified.

To assess the floral diversity, a detrended correspondence analysis (DCA) (Hill and Gauch, 1980) was used to explore the main gradients of plant community variability in the grazed and non-grazed pastures. DCA was calculated in R using the vegan package (Oksanen et al., 2015) with data obtained from plant diversity indicators based on Albuquerque et al. (2010). The absolute frequency (Fa, Equation (1), the relative frequency (Fr, equation (2), the absolute dominance (Doa, equation (3), the relative dominance (Dor, equation (4) and the importance value (IV, Equation (5) were calculated from the obtained samples for each species:

$$Fa_i = (n_i/N) \bullet 100 \tag{1}$$

Where Fa_i = Absolute frequency of species i; ni = number of sample units where species i was found; N = total number of sample units.

$$Fr_i = \left(\frac{FA_i}{\sum Fa}\right) \bullet 100 \tag{2}$$

Where Fr_i = Relative frequency of species i; Fa_i = Absolute frequency of species i; $\sum$ Fa = summation of the absolute frequencies of the species.

$$Doa_i = \left(\frac{\sum PC_i}{N}\right) \bullet 100 \tag{3}$$

Where Doa_i = Absolute dominance of species i; PCi = percentage of coverage of the species per sampled unit; N = total number of sample units.

$$DoRi = \left(\frac{DoAi}{\sum Doa}\right) \bullet 100 \tag{4}$$

Where Dor_i = Relative dominance of species i; Doa_i = absolute dominance of species i; $\sum$ Doa = total of the absolute dominance of the species.

$$IV_i = (Fr_i + Dor_i)/2 \tag{5}$$

Where IV_i = Importance value index of species i; Fr_i = Relative frequency of species i; Dor_i = Relative dominance of species i.

Species diversity was also calculated for each habitat using the Shannon-Wiener index (H', equation (6) (Shannon and Weaver, 1949), and Pielou's equity index (J', equation (7) (Pielou, 1966), according to the formulas:

$$H' = -\sum pi(lnpi) \tag{6}$$

Where H' = Shannon-Wiener diversity index; pi = relative dominance of species i; ln pi = Neperian logarithm of pi.

$$J' = \frac{H'}{lnS} \tag{7}$$

Where J' = Pielou's equity index; H' = Shannon–Wiener diversity index; S = total number of sampled species; ln S = Neperian logarithm of S. The Pielou index measures the proportion of the observed diversity in relation to the maximum expected diversity. Its value ranges from 0 to 1, so that 1 corresponds to situations where all species are equally

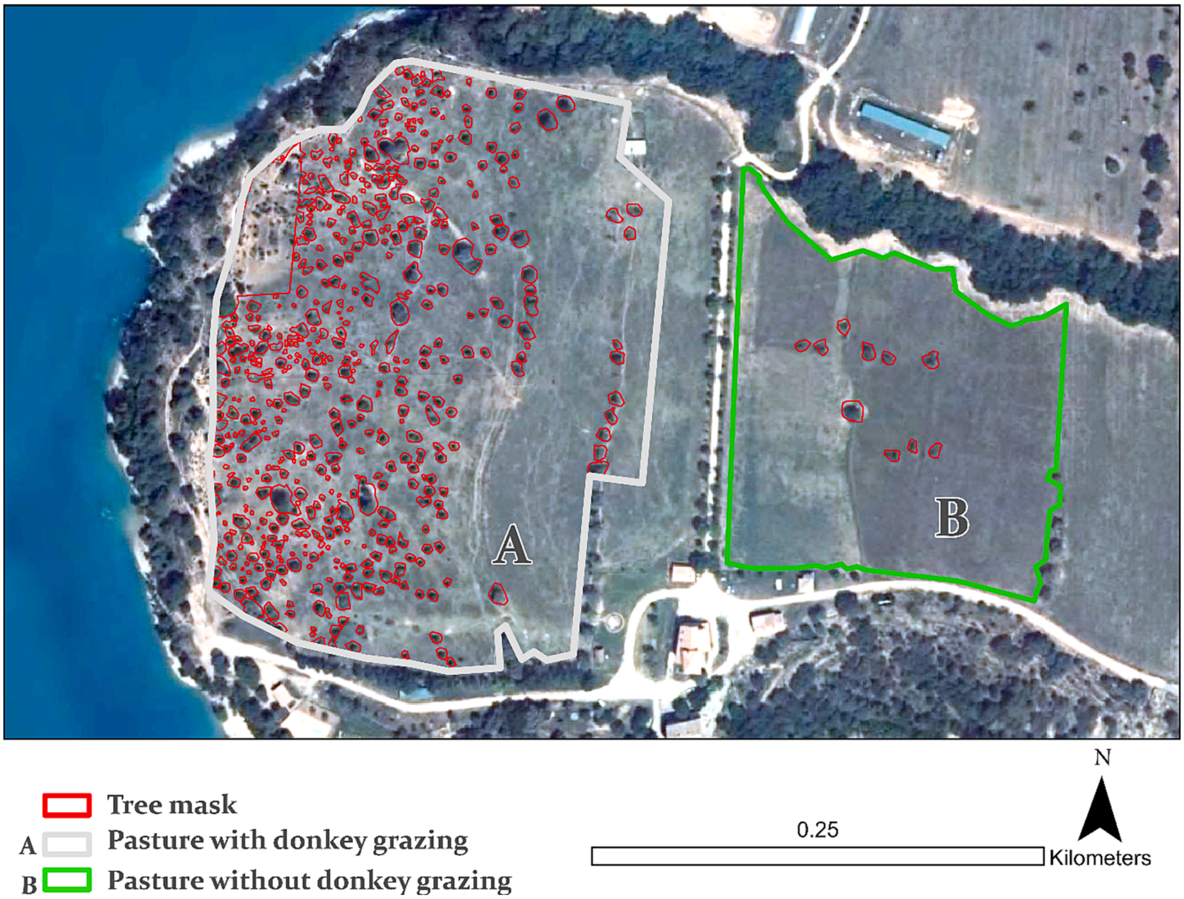

Fig. 4. Pasture with donkey grazing indicated with an A and the control pasture B without donkey grazing are shown. Tree mask is also delineated in red. The background image is an aerial orthophoto composition generated by the Spanish National Plan of Aerial Orthophotography in 2018. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

abundant.

To interpret the floristic similarity between the plots, the Jaccard similarity index (ISj, equation (8) (Jaccard, 1908), was used as a measure of distance. The similarity index (ISj) was also used to compare the analyzed habitats.

$$ISja, b = C/A + B + C \tag{8}$$

Where ISj a, b = floristic similarity by means of the Jaccard index between habitats a and b (pastured and not pastured); C = number of species common to both habitats; A = number of species exclusive to habitat a; B = number of species exclusive to habitat b.

2.3. Remote sensing data and processing

To assess land use changes in Puy de Cinca, we used two aerial scenes, one from 1956 and the other from 2018 at 0.5 m spatial resolution. The images were downloaded from the regional Aragon government geodata server for the municipality of Secastilla where Puy de Cinca is located (https://idearagon.aragon.es/fichaDescarga/fichaDescarga_22214.html). The 1956 image is now publicly available, a black-and-white photograph originally captured by a military aircraft. The 2018 scene was captured within the National Plan of Aerial Orthophotography from the Spanish Government; it is a red–green–blue orthophoto. In both cases, forest areas were mapped by establishing a threshold pixel value, 100 points distributed in the forest landscape were visually spotted and averaged to obtain the pixel value thresholds to differentiate forested areas from other land uses in 1956 and 2018. In the case of the 1956 photograph, pixels between 0 and 100 values were considered forested areas, while in the 2018 orthophoto, pixels between 15 and 85 values were considered forested areas. This processing was carried out in ArcGIS Pro 3.1.0. by selecting a logical expression that selects a subset of raster cells within the stablished thresholds, and subsequently the forested areas in both periods were quantified with the corresponding confidence intervals according to Olofsson et al. (2014). Moreover, agricultural lands in 1956 were visually delineated and compared to current declared agricultural activities within geographic information systems of the common agrarian policy of the European Union, obtained at https://idearagon.aragon.es/descargas. We decided to visually delineate the agricultural areas because the spectral resolution of the black-and-white 1956 scene did not provide enough information to calculate an accurate classification algorithm. We therefore assessed the agricultural land from previous documents and direct consultation with locals to focus on specific areas; riverbanks and terraced hills close to the settlements. Trails were delineated based on 1956 aerial images and compared to the current trails. A visual example of what was delineated as trails in the 1956 aerial images is shown in the appendix (Fig. A1).

The classification of forest changes in the two scenes (1956 and 2018) was re-classified into four categories to improve the assessment of forested area and its classification accuracy: no forest, namely pixels that currently do not host forest and did not host forest in the 1956 scene; forest loss, where forest pixels identified for 1956 were lost by 2018; forest gain, where forest pixels gained by 2018 contrasted with forest absence in 1956; and stable forest, with forest pixels that were stable across the studied time period. To assess the accuracy of the classification of forest changes, a confusion matrix was computed by assessing 150 random points on ArcGIS Pro 3.1.0. The accuracy assessment obtained from the confusion matrix was used to calculate the areas for each

Table 1
Phytosociological parameters of the identified species and those not identified in donkey-grazed pasture. The parameters are ordered from the highest to the lowest importance value (IV). Absolute frequency (Fa), relative frequency (Fr), absolute dominance (Doa), and relative dominance (Dor) are also shown.

Species	Fa (%)	Fr (%)	Doa (%)	Dor (%)	IV (%)
Medicago minima	100	5.78	61.5	19.15	12.46
Cynodon dactylon	100	5.78	55	17.12	11.45
Medicago rigidula	100	5.78	32.1	9.99	7.89
Plantago lanceolata	100	5.78	21.5	6.69	6.24
Knautia arvensis	100	5.78	18.6	5.79	5.79
Sanguisorba minor	90	5.20	17.2	5.35	5.28
Salvia verbenaca	100	5.78	14.5	4.51	5.15
Dactylis glomerata	100	5.78	9.4	2.93	4.35
Crepis capillaris	80	4.62	12.7	3.95	4.29
Sherardia arvensis	80	4.62	4.6	1.43	3.03
Hypochaeris radicata	70	4.05	4.4	1.37	2.71
Urospermum picroides	80	4.62	1.6	0.50	2.56
Aegilops geniculata	40	2.31	8.8	2.74	2.53
Potentilla reptans	30	1.73	10.3	3.21	2.47
Trifolium pratense	20	1.16	10.5	3.27	2.21
Bromus erectus	50	2.89	3.1	0.97	1.93
Torilis nodosa	40	2.31	4.7	1.46	1.89
Galium album	30	1.73	5	1.56	1.65
Centarium tenuiflorum	40	2.31	1.1	0.34	1.33
Not identified 1	40	2.31	0.8	0.25	1.28
Eringium campestre	40	2.31	0.8	0.25	1.28
Hypericum perforatum	20	1.16	4.3	1.34	1.25
Brachypodium phoenicoides	10	0.58	6	1.87	1.22
Malva sylvestris	30	1.73	1	0.31	1.02
Anagallis foemina	30	1.73	0.8	0.25	0.99
Ononis repens	30	1.73	0.7	0.22	0.98
Euphorbia falcata	20	1.16	1.8	0.56	0.86
Pethroragia sp.	20	1.16	0.7	0.22	0.69
Koelleria vallesiana	20	1.16	0.6	0.19	0.67
Lotus corniculatus	20	1.16	0.5	0.16	0.66
Not identified 2	10	0.58	2	0.62	0.60
Silene vulgaris	10	0.58	2	0.62	0.60
Alyssum alyssoides	10	0.58	1	0.31	0.44
Not identified 3	10	0.58	0.3	0.09	0.34
Medicago sativa	10	0.58	0.3	0.09	0.34
Geranium molle	10	0.58	0.2	0.06	0.32
Carex sp.	10	0.58	0.2	0.06	0.32
Hippocrepis unisiliquosa	10	0.58	0.2	0.06	0.32
Dead plant	10	0.58	0.2	0.06	0.32
Achillea millefolium	10	0.58	0.2	0.06	0.32

of the four forest classes with corresponding confidence intervals. Error margins at 95 % probability for each class were derived from the set of error pixels and matched pixels according to the following equations (equation (9):

$$S(\widehat{A}_k) = A \times S(\widehat{p}_{\bullet k}) \tag{9}$$

Where $\hat{A}_k$ is the estimated area of the mapped change class k (in our case it has four classes), A is the total map area, $\widehat{p}_{\bullet k}$ is the estimated area proportion of change in class k derived from the error matrix (see notations in Olofsson et al., (2014): Eqs. (9), 10 and 11), page 52), and S is the standard error function of the estimators. $S(\widehat{p}_{\bullet k})$, shown in equation (10), is the standard deviation of the area proportion of the corresponding class. An approximate 95 % confidence interval is obtained as $\hat{A}_k \pm 1.96 \times S(\hat{A}_k)$.

$$S(\widehat{p}_{\bullet k}) = \sqrt{\sum_i W_i^2 \frac{\frac{n_{ik}}{n_i}\left(1 - \frac{n_{ik}}{n_i}\right)}{n_i - 1}} \tag{10}$$

As an indicator of biomass cover in pastured and non-pastured pastures, Sentinel-2 images were downloaded free of clouds on the Copernicus Open Access Hub (https://scihub.copernicus.eu/), for the grazing period June to September 2020, during the donkeys' presence, and we obtained 12 images (24 June, 29 June, 19 July, 29 July, 8 August, 23 August, 27 August, and 12 September). Moreover, we also downloaded images (9) in previous and subsequent months to see the evolution of the pastures throughout the year (31 January, 10 February, 20 February, 21 March, 20 May, 30 May, 17 October, 21 November, and 26 December). These images were downloaded as Sentinel-2 2A bottom-of-reflectance products, which are already corrected for atmospheric interference. Two bands were used, red (Band 4) and near-infrared (Band 7) at 10 m spatial resolution to obtain a biomass indicator of pastured and non-pastured pastures. Subsequently, the normalized difference vegetation index (NDVI) (Rouse et al., 1974) was used because it is widely applied as a biomass indicator for forest cover and pastures (Maselli et al., 1998). The NDVI (Equation (11) was calculated for all the dates mentioned in the two pastures shown in Fig. 4. Moreover, due to the presence of large trees within the pastures, trees were masked to differentiate them from pasture pixels and avoid interferences in NDVI calculations (Fig. 4). In the pastured area (A in Fig. 4), the same eight donkeys mentioned in the description of the floral diversity assessment were present and grazing, while in the non-pastured area, no donkeys were present. We decided to use these two pastures to determine biomass when grazing because the control pasture had some recovery in previous years (it had been grazed in the previous 2019 season). Meanwhile, the abandonment of the pasture used for the floristic diversity difficulted observing remotely the pastured area due to the occurrence of shrubs and trees.

Table 2
Phytosociological parameters of the identified species in the abandoned pasture without grazing donkeys. The parameters are ordered from the highest to the lowest value of importance (IV). Absolute frequency (Fa), relative frequency (Fr), absolute dominance (Doa), and relative dominance (Dor) are also shown.

Species	Fa (%)	Fr (%)	DoA (%)	Dor (%)	IV (%)
Brachypodium phoenicoides	70	11.29	43.4	31.40	21.35
Knautia arvensis	70	11.29	19	13.75	12.52
Galium album	90	14.52	13	9.41	11.96
Dorycnium hirsutum	70	11.29	14	10.13	10.71
Odontites luteus	60	9.68	11.3	8.18	8.93
Eringium campestre	40	6.45	8	5.79	6.12
Pilosella officinarum	30	4.84	9.8	7.09	5.96
Plantago lanceolata	40	6.45	4.3	3.11	4.78
Agrimonia eupatoria	40	6.45	0.4	0.29	3.37
Catananche caerulea	20	3.23	4.7	3.40	3.31
Sanguisorba minor	30	4.84	2.2	1.59	3.22
Prunella laciniata	10	1.61	2	1.45	1.53
Genista scorpius	10	1.61	2	1.45	1.53
Lavandula latifolia	10	1.61	2	1.45	1.53
Potentilla reptans	10	1.61	1.5	1.09	1.35
Hippocrepis unisiliquosa	10	1.61	0.3	0.22	0.91
Medicago sativa	10	1.61	0.3	0.22	0.91

$$NDVI = \frac{(NearInfraredB8 - RedB4)}{(NearInfraredB8 + RedB4)} \tag{11}$$

3. Results

A total of 56 floral species (Tables 1 and 2) were detected in pastures with and without donkey grazing, from which 39 grew in the donkey-grazed pasture and 17 grew in the abandoned pasture. Hence, the number of species found in the pasture with donkeys was 56 % greater than the number of species in the abandoned pasture. In the donkey-grazed pasture three species could not be identified as the plants did flower or bear fruit, and therefore could not be classified. From the total number of species registered, 34 were identified to the specific level and represented 18 botanical families. In the donkey-grazed pasture the 18 botanical families were present, but the abandoned pasture only had 9. The most abundant families were Asteraceae (7), Poaceae (6) and Fabaceaea-Faboidae (9).

The species with the highest IV in the donkey-grazed pasture were *Medicago minima, Cynodon dactylon, Medicago rigidula, Plantago lanceolata* and *Knautia arvensis* (Table 1). Meanwhile, in the abandoned pasture the species that had the highest IV were: *Brachypodium*

Table 3
Number of species (S). Shannon-Wiener (H′) biodiversity index and Pielou (J′) index for the donkey-grazed pasture and the abandoned pasture.

Habitat	S	H'	J'
Donkey-grazed pasture	39	2.77	0.76
Abandoned pasture	17	2.21	0.78

Table 4
Confusion matrix for the forest change map 1956–2018 shown in Fig. 5. Users accuracy (UA), producers accuracy (PA), and overall accuracy (OA) are shown, with 150 pixels being used for the accuracy assessment.

	No forest	Forest loss	Forest gain	Stable forest	UA [%]
No forest	19	2	0	0	90.5
Forest loss	2	9	0	1	75.0
Forest gain	0	0	59	5	92.2
Stable forest	0	0	8	45	84.9
PA [%]	90.5	81.8	88.1	88.2	OA = 88.0

phoenicoides, Knautia arvensis, Galium sp., *Dorycnium hirsutum* and *Odontites luteus* (Table 2). The IV of the first five species was higher in the abandoned pasture than in the donkey-grazed pasture. In the abandoned pasture, *Brachypodium phoenicoides* had the highest IV value (IV = 21.35 %), whereas in the donkey-grazed pasture *Medicago minima* had the highest (IV = 12.46 %). In all cases, the IV was different for the equivalent species between the abandoned pasture and the donkey-grazed pasture. Moreover, the species with the highest IV values differed between the abandoned pasture and the donkey-grazed pasture.

Among the group of species with the lowest IV values, however, some species were equivalent between the pastures (*Potentilla reptans, Hippocrepis unisiliquosa*, and *Medicago sativa*). Nonetheless, in absolute numbers they were not the same. The low number of species found in the abandoned pasture and the high IV values among the most abundant species indicated the dominance of certain species. In contrast to the abandoned pasture in which *Brachypodium phoenicoides* dominated, in the donkey-grazed pasture this species had a VI of 1.22 %, which represents a 17-fold decrease relative to the abandoned pasture.

Regarding phytosociology, the Shannon-Winer (H′) and Pielou (J′) indices in the donkey-grazed pasture were H′ = 2.77 and J′ = 0.76, compared to the values of H′ = 2.21 and J′ = 0.78 in the control pasture (Table 3). The results suggest that a higher floral diversity was found in the donkey-grazed pasture in comparison with the abandoned pasture. Moreover, the plant community was more heterogenous in the donkey-grazed pasture, with J′ = 0.76, than in the abandoned pasture J′ = 0.78 (Table 4). These indices indicated the presence of more species with less relative dominance values in the donkey-grazed pasture, which result in a better species diversity and a heterogenous vegetal community. From the 56 species in both pastures, only 9 were common to the two, which resulted in a 18.75 % of similarity under the Jaccard Similarity index (ISJa,b = 0.1875). In fact, 31 species are specific to the donkey-grazed pasture and 8 are specific to the abandoned pasture. In two pastures located so close together, one would expect a similar composition;

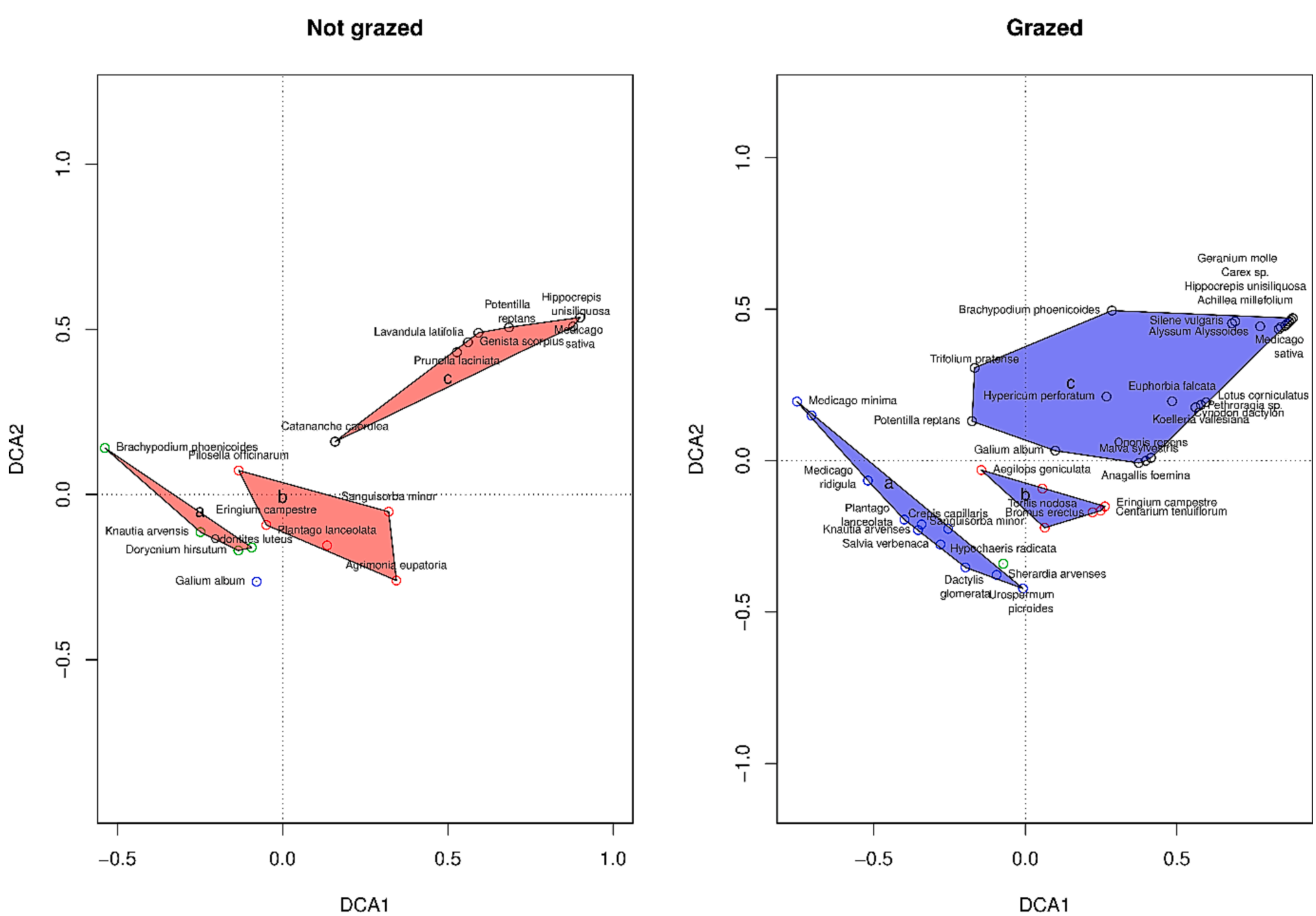

Fig. 5. Detrended correspondence analysis (DCA) ordination of plant communities in the grazed and non-grazed pasture. In both cases the DCA2 and DCA1 axes were selected to explain most of the variance. The color of the points indicates the grouping of species in each pasture, and the species name of each point is indicated with a label.

Table 5
Estimated area and confidence intervals of forest classes calculated according to Olofsson et al. (2014) from the map shown in Fig. 6 and the accuracy assessment obtained with the confusion matrix shown in Table 1.

Class	Estimated area (ha)	Confidence intervals (ha)
No forest	188.4	33.6
Forest loss	78.1	32.9
Forest gain	348.3	17.0
Stable forest	242.4	53.6

nonetheless, it seems that the donkeys' grazing influenced the floral diversity.

In this sense, the DCA results in Fig. 5 show a clear separation among the compositions of three plant communities in each pasture. In the non-grazed DCA plot, the DCA1 axis explained 63 % and the DCA2 axis 36 % of the total variability in the species dataset. Meanwhile, in the grazed DCA plot, the DCA1 axis explained 59 % and the DCA2 axis 22 % of the total variability in the species dataset. In the grazed pasture, species with lower frequencies showed higher floristic variation than in the non-grazed pasture. Regarding the community formed by the most common species, the grazed pastures showed a greater diversity than the non-grazed pasture (Fig. 5).

In the case of forest change, the classification we calculated achieved a relatively high overall accuracy of 88 % (Table 4). In general, all forest change classes have been correctly classified. The forest loss class was the least well classified, with some misclassification having occurred because the forest loss areas were minimal and mainly located along the former riverbank and some roads developed in recent times. Moreover, this class was susceptible to misclassifications due to shaded pixels, especially related to single trees. The estimated areas and confidence intervals calculated for each forest change class are shown in Table 5 and mapped in Fig. 6. The largest area estimated corresponds to forest gain (348.3 ± 17.0 ha), the second to stable forest area (242.4 ± 53.6 ha), the third to no forested area (188.4 ± 33.6 ha), and the fourth to forest loss (78.1 ± 32.9 ha). In terms of other land uses, agricultural land encompassed 114.25 ha in 1956, with most agricultural fields located in terraces (90.25 ha) and a minority (24 ha) located in lowlands (Fig. 7), mainly by the riverbank. In 2020 there were 31 ha of agricultural land, mainly comprised of olive trees followed by vineyards (Fig. 7), of which only 2.3 ha were not croplands in 1956. The reduction in agricultural land over six decades has been 73 %, with only 28.7 ha of stable cropland. Regarding the trails that connect different parts of the village

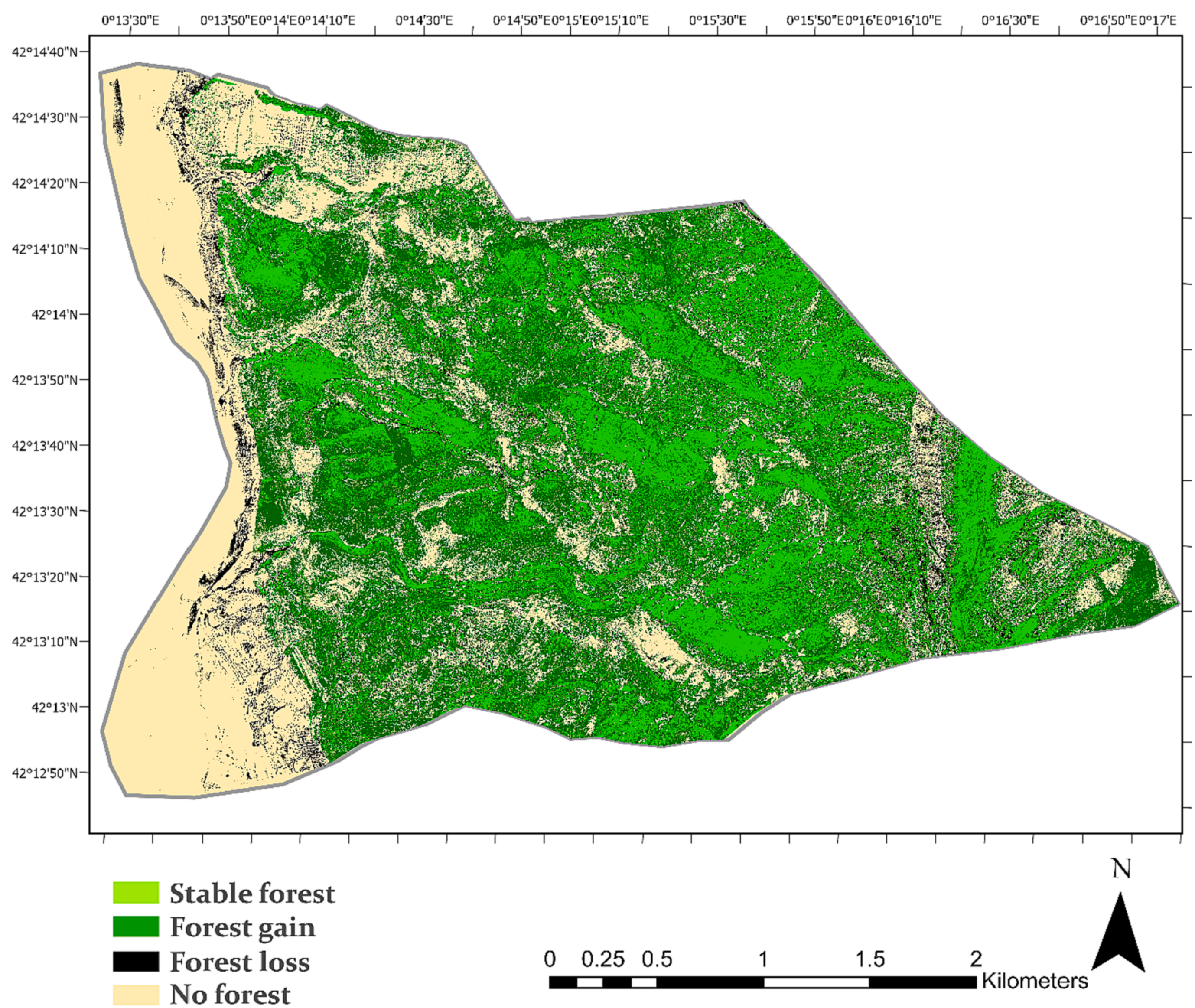

Fig. 6. Forest change map for the period 1956–2018, four classes are represented in the map: stable forest, forest gain, forest loss and no forest.

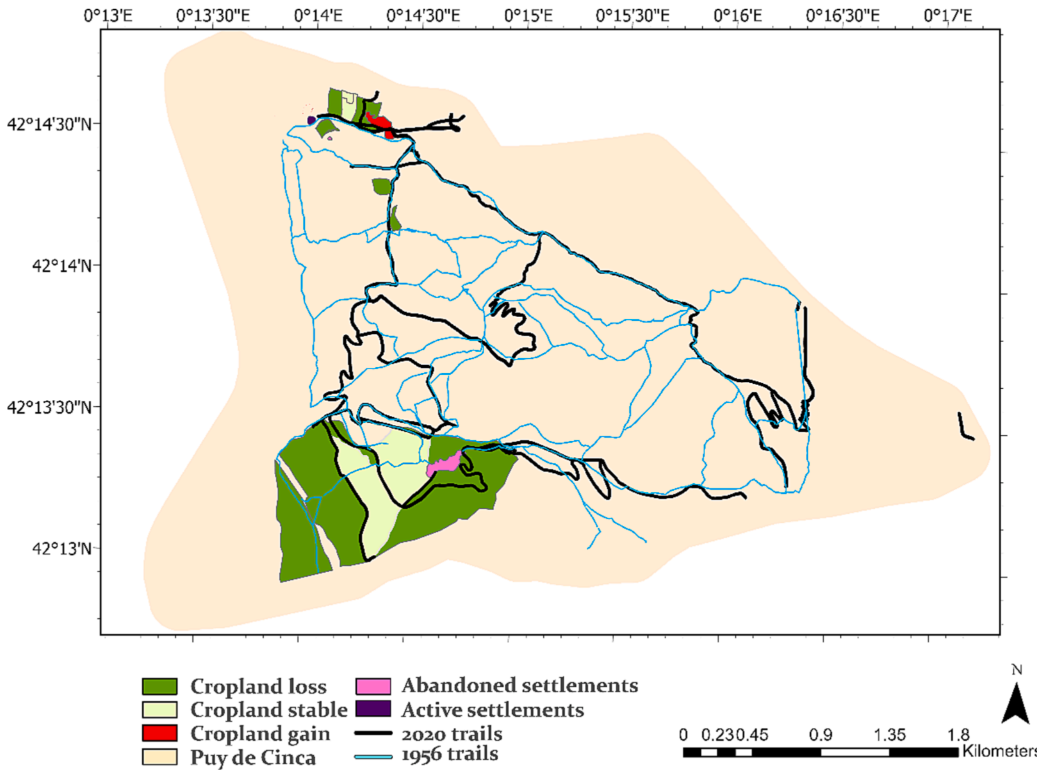

Fig. 7. Changes in cropland, settlements, and trails in Puy de Cinca from 1956 to 2018.

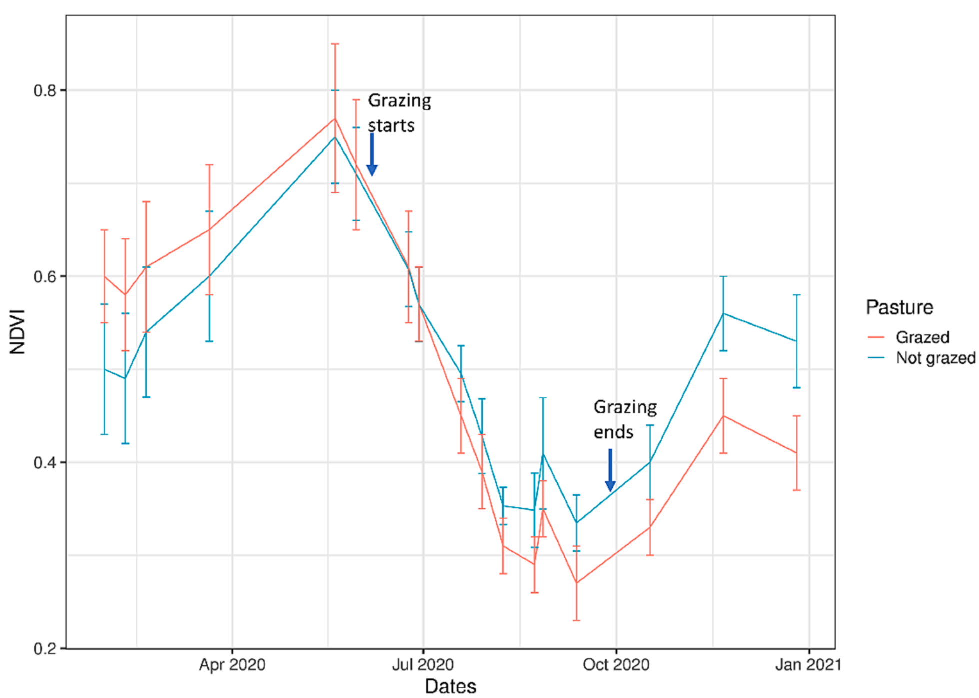

Fig. 8. Pattern of evolution of the NDVI from the control pasture (without grazing) and the donkey-grazed pasture.

territory, 88 km of trails were delineated in the aerial photographs from 1956, while the current (2022) trails only extend 33 km. This is a 62.5 % reduction in trail length over six decades (Fig. 7).

Before donkey grazing commenced, the NDVI values suggested that biomass and phytovolume in the grazed pasture was larger (Fig. 8). When the donkeys started grazing in June, the NDVI values for the 24th of June (2020) were similar in both the grazed and non-grazed (i.e. control) pastures, with values of 0.61 ± 0.04 and 0.61 ± 0.06 respectively. On the 19th of July, the NDVI values suggested a change in the biomass of the pastures, likely due to the grazing activity, with a lower NDVI in the grazed, (0.45 ± 0.02), than in the non-grazed pasture (0.50 ± 0.03). This trend continued throughout the studied period, with the donkey-grazed pasture having lower NDVI values. In addition, environmental factors such as rainfall affect plant vigor, especially in

Mediterranean summers. Due to summer rain, an increase in biomass was observed between 23 August and 27 August. The NDVI value was nonetheless equally lower in the donkey-grazed pasture (Fig. 8). After grazing ended in the pasture the subsequent NDVI values were still lower in the previously grazed pasture than in the non-grazed pasture.

4. Discussion

Regarding the first research question, "how much has the traditional landscape changed since the mid twentieth century (1956–2018) in Puy de Cinca?", significant changes have been observed. This is, especially the case for forest changes, including an increase over that period of 348.3 ± 17.0 ha in the forest cover, a 73 % reduction in agricultural land, and a 62.5 % reduction in trail length. These findings in Puy de Cinca align with a study on land use changes for a larger area elsewhere in Ribagorça county (the same county where Puy de Cinca is located), which showed a reduction of 50 % in agricultural land and a six-fold increase in forest area, including active reforestation (Sancho-Reinoso, 2013). In that study, the most extreme changes were observed in the mountainous areas rather than in the valleys of Ribagorça. The reduced forest cover that we observed from 1956 could be explained by several factors, such as the demographic pressure of the time and the need to obtain fuelwood and charcoal, which was also significant due to the abundance of oak forests (Solé i Sabarís, 1962). In that sense, the main drivers of forest expansion and agricultural decrease in Puy de Cinca might be linked to economic and water policies, plantation of fast-growing tree species, and rural depopulation. These changes are also observed with the number and extent of trails connecting different parts of the village with the former riverbanks, scrublands, forests, and agricultural lands that have disappeared. The trails, which were mainly used for human and animal transportation, have reverted to forest or scrublands due to the abandonment of agricultural fields and pastures. Among the several factors that have triggered the degradation of Puy de Cinca's traditional landscape, we argue that a key factor has been the destruction of the agricultural landscape along the riverbanks. The construction of the dam not only put these areas under water, but also changed the relationship to the main source driving the agrarian economy. Water management changed from a locally focused model agreed through communities of irrigators and their traditional ecological knowledge, to a more centralized management model (Bergua Amores, 2006).

Understanding landscape changes is a key factor to recover its functions. Indeed, traditional landscapes have been shaped by a prolonged human-environment interaction. Such a sustained relationship between people and the land, generates a profound knowledge of the territory (Oteros-Rozas et al., 2013; Reyes-García et al., 2014) regarding the distribution of species, the presence of pastures, the availability of water or the network of pathways for livestock and transportation. After the abandonment of villages and loss of bio-cultural knowledge, the reconstruction of these traditional landscapes is a challenge. In the case of Puy de Cinca, we have observed that remote sensing temporal images can contribute to rediscovering these land use changes. Furthermore, remotely sensed observations of changes in the landscape can guide policy implementation for the recovery of traditional landscapes and the withdrawal of damaging policies in the territories, as has been done elsewhere (González-Fernández et al., 2022; Osorno-Covarrubias et al., 2018). Capturing aerial or satellite scenes throughout time allows monitoring of temporal changes in Mediterranean landscapes (Lasanta and Vicente-Serrano, 2012; Zomeni et al., 2008). Moreover, remote sensing data allows monitoring of vegetation cover and understanding of agricultural lands and vegetation biophysical parameters such as biomass and other significant parameters for pasture management (von Keyserlingk et al., 2021).

Regarding the second research question, "does the grazing of Catalan donkeys reduce pasture biomass and phytovolume?", differences in the NDVI, as a proxy for the photosynthetically active biomass and phytovolume of the pastures, were observed with Sentinel-2 satellite imagery between grazed and non-grazed pastures. Indeed, the evolution of NDVI values throughout the grazing season suggested that the donkeys did impact the pasture's photosynthetically active biomass and phytovolume. However, NDVI values derived from Sentinel-2 spectral data showed some limitations when attempting to clearly distinguish between the grazed and non-grazed pastures. These limitations might be linked to the presence of trees and the lack of signal from the tree understory as well as the spatial resolution of the pixels (10 m), which might be limited to pick up the necessary fine details to accurately assess the effects of grazing. At the same time, the low-to-moderate-intensity of grazing might have made it challenging to sense changes in pasture biomass and phytovolume. The capacity of satellite imagery to monitor biophysical parameters related to biomass, such as the NDVI, has been effective at demonstrating the impact of large herbivores, other than donkeys, on pastures (Balata et al., 2022; Catorci et al., 2021; Navarro et al., 2020). Moreover, other articles have addressed donkey grazing as a forest management strategy and observed a reduction in flammable species in mountainous areas (Gartzia et al., 2009). Our results suggest the potential of Sentinel-2 data for monitoring low-to-moderate-intensity donkey grazing, with some limitations that could be improved by extending the number of pastures and seasons, as well as using broader spectral information, because high-resolution commercial satellites are not a current option for monitoring vegetation covers due to the existence of paywalls for accessing the images (Francini et al., 2020). The capacity to monitor the biomass with remote sensing data allows assessing the grazing impacts within the landscape. This entails significant implications in spatially controlling pastures biomass and flammable grasses for forest risk management in the case of Puy de Cinca and other equivalent sites.

Therefore, monitoring pastures with satellite images, and particularly the exploitation of the temporal and spatial resolution of freely accessible Sentinel-2 imagery (Segarra et al., 2020), can assist with monitoring of biomass changes in donkey-grazed pastures, and also contribute to controlling the expansion or decline of forests and scrublands. At the same time, the recovery of trails within the traditional landscape should re-connect pastures and reestablish some agricultural land in terraces that require some animal traction due to the narrow nature of the fields. This has already been addressed in recent years by some farmers within the same province (Huesca) who are using horses in narrow vineyards and vegetable gardens with significant benefits regarding sustainable practices. Moreover, other alternatives for animal traction, such as the use of Catalan donkeys, could add value to the reestablishment of crops in these mountainous areas, and help continue this uniquely adapted breed.

Regarding the third research question, "is floral diversity in pastures with grazing donkeys greater than in abandoned pastures?", an important result of the study is that the floristic composition of a donkey-grazed pasture showed greater diversity than an abandoned pasture without donkey activity. This aligns with other studies reporting higher plant diversity in low-intensity pastures with grazing by large herbivores such as horses (Köhler et al., 2016; Moinardeau et al., 2020), or a combination of cattle with occasional donkey grazing (Török et al., 2016), in contrast to non-grazed or intensively grazed pastures. Such studies, nonetheless, were carried out in relatively wet central European climates, which can be classified as possessing productive grasslands. Some authors argue that grazing by large herbivores enhances plant diversity, particularly in productive environments (Catorci et al., 2012). However, in poorer soils, grazing may negatively affect plant species richness, where soil resources limit the regrowth of plant species (Proulx and Mazumder, 1998). In the current study, our findings for a Mediterranean mountainous landscape in northeast Spain, suggest that donkey grazing can also contribute to enhance biodiversity by recovering plant diversity and improving forage value. Indeed, two of the three most abundant plants found in the grazed pasture are from the *Medicago* genus, which has high potential for seed and forage production (Porqueddu and González, 2006). Moreover, the second most abundant species was *Cynodon dactylon*, which also has a high forage value and is adapted to Mediterranean environments. This species normally appears on well-formed soils where the impact of summer droughts can be counteracted by the development of a deeply penetrating root system reaching the water table (Galiano, 1985). In contrast, in the abandoned pasture, the most abundant species was *Brachypodium phoenicoides,* belonging to the Gramineae family, and it has a relatively low nutritional value compared to other species growing in Mediterranean pastures (Viano et al., 1996). The second most abundant species in the abandoned pasture was *Knautia arvensis*, which has also been described elsewhere in non-grazed pastures due to its ability to spread by clonal growth, resulting in higher competitive advantage in the plant community (Stránská, 2004). Comparing the presence of the *Plantago* genus between the abandoned and grazed pasture, the dominance of *Plantago lanceolata* was also greater in the grazed pasture, and it is known for being sensitive to shading, so a reduction in plant phytovolume following grazing by donkeys likely contributed to its development. Moreover, it produces nutritional forage for grazing animals (Stewart, 1996).

Donkey breeds are scarce in the Iberian Peninsula, but they exhibit more specialized distributions than other livestock and are adapted to a wide range of environmental heterogeneity (Alonso et al., 2022). For this reason, Catalan donkeys may contribute towards the recovery of traditional landscapes through their adaptation to the specific environment of Mediterranean mountains, increasing floral diversity in pastures, and reducing the tree understory while improving forest management with implications for fire risk reduction. Nevertheless, there are some limitations to this study, first regarding the number of Catalan donkeys available, and second, the spatial analysis that could be achieved of their effect on pastures and species diversity, which was confined to the northern part of the village and to a few pastures. Moreover, donkeys exhibit a preference for grassy species and do not graze significantly on scrubs, unlike other animals. Consequently, donkey grazing with other animals (such as goats) could function synergistically (Bartolomé et al., 2020) for the recovery of traditional mountain landscapes. Furthermore, combining several grazing animal species would increase the capacity of such environmental management strategies because the current donkey population is too small to cover the entirety of Puy de Cinca. Additionally, due to their preference for specific grass types and the resulting uneven grazing (Gartzia et al., 2009), the geolocation of donkeys and the use of satellite images to monitor their free grazing activity could help determine biomass accumulation and then coordinate management of other animals across the landscape.

Besides grazing, the findings of this study suggest that a general political change regarding mountainous rural areas could be addressed. The most important changes in these landscapes happened more than half a century ago in a centralized dictatorial Spain, which since then has continued to shape most rural areas with characteristic depopulation and poor income opportunities, as well as the loss of bio-cultural knowledge. Furthermore, in more recent decades, the few abandoned mountain villages recovered by people have continued to suffer political ambiguity and even adversities; in fact, after the restauration of democracy, Spanish politics has neglected, and even negated, mountain identities and ways of living. The main initiatives regarding the conservation of the Catalan donkey landrace and the recovery of abandoned villages such as Puy de Cinca is based on grass-roots activism from the few people remaining in the area who wish to preserve and recreate traditional approaches to living in the landscape and manage the mountain territory. In this sense, several workshops regarding the use of Catalan Donkey have been carried out in Puy de Cinca, and the use of satellite data to monitor and preserve the environment have been discussed with locals through a dialogue of voices. We see this as a critical application of remote sensing, as described by Bennett et al. (2022), which simultaneously exposes injustices, reflexively engages with situated local knowledge, and expands access to geospatial technologies.

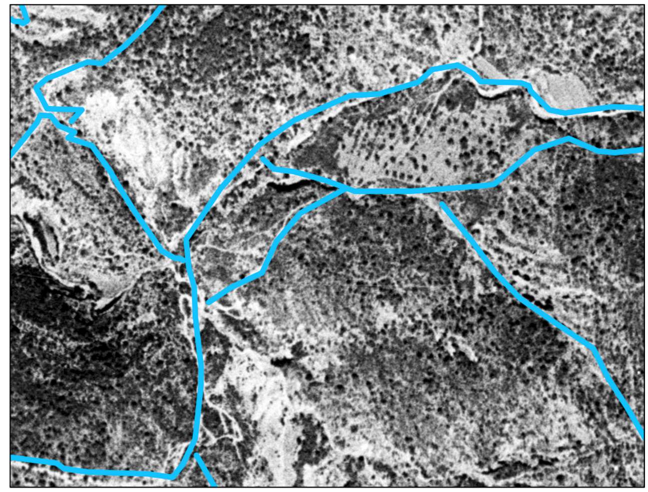

Fig. A1. An example of the delineation of trails in a scene from 1956 is shown. Only long trails connecting different points of the studied areas were delineated, and shorter paths (as observed in the Figure) were not delineated as they did not represent the general network of connection in the landscape. Narrow long path-like shapes were considered trails and delineated visually.

The recovery of traditional mountain landscapes will benefit from a dialog of locals with remote sensing scholars.

5. Conclusion

We conclude that, at low-to-moderate-intensity grazing, Catalan donkeys help to reduce phytovolume and biomass and enhance plant diversity in pastures. The recovery of the endangered donkey landrace could play a relevant role in the environmental management of the abandoned mountainous Mediterranean landscape that we have studied in northeast Spain (Puy de Cinca). The landscape changes we quantified, including an increase in forest cover (348.3 ± 17.0 ha), a 73 % loss of croplands and a 62.5 % reduction in the trails interconnecting the territory, illustrates a loss of the landscape's original functions. We have proven, with some limitations, the suitability of Sentinel-2 images to detect reductions in biomass due to donkey grazing activity. The study may also be useful for other cases where the degradation of traditional landscapes in Mediterranean mountainous areas is significant and the recovery of animal landraces could help restore these landscapes and provide continuing environmental and ecosystem services.

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

All data used is publicly available

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Appendix

See Fig. A1.

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