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Have Historical Land Use/Land Cover Changes Triggered a Fire Regime Shift in Central Spain?

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Abstract: Fire is one of the main disturbance factors shaping the landscape, and landscape is a key driver of fire behavior. Considering the role played by land use and land cover (LULC) changes as the main driver of landscape dynamics, the aim of this study was to calculate and analyze (i) the real impact of fire on LULC changes and (ii) how these LULC changes were influencing the fire regime. We used methods of historical geography and socio-spatial systemic analysis for reconstructing and assessing the LULC change and fire history in six case studies in the Central Mountain System (Spain) from archival documentary sources and historical cartography. The main result is an accurate dataset of fire records from 1497 to 2013 and a set of LULC maps for three time points (1890s–1930s, 1956–1957, and the 2000s). We have shown the nonlinear evolution of the fire regime and the importance of the local scale when assessing the interaction of landscape dynamics and fire regime variation. Our findings suggest that LULC trends have been the main influencing factor of fire regime variation in Central Spain since the mid-19th century.

Keywords: Central Mountain System; fire history; geohistorical sources; Iberian Peninsula; landscape dynamics; Pyrogeography; local scale; LULC

1. Introduction

Fire is one of the main natural disturbances that shape the landscape, and landscape, combined with weather and climatic conditions, is the main driver of fire behavior [1–3]. Yet, while fire has been largely studied as a landscape disturbance factor [4], landscape influence on fire regimes has not received the same attention [5,6]. One of the reasons is that research on the effect of social-ecological contextual factors on fire regime change requires a long-term and local scale approach. That means that a strong data limitation constraint has to be dealt with, and that it is difficult to make generalizations based on the modeling of the site-specific results obtained [7–9].

In fact, the historical effect of fire on the vegetation cover has been extensively investigated worldwide [10–12]. In Central Spain, several studies based on paleopalynological analyses have found a strong connection between human activity, namely land use history, fire impact, and the configuration of forest vegetation during the last millennia [13–20]. Additionally, palaeoecological methods were applied in Sardinia to demonstrate the effects of long-term fire history on vegetation under changing Holocene climates and land use [21]. Other studies have also provided evidence of the effect of land use and land cover (LULC) changes on the fire regime [22,23]. Nonetheless, most of these studies use geostatistical and remote sensing methods, which limits the temporal analysis scale to the second half of the 20th century and the early 21st century [24–31].

Furthermore, recent studies have illustrated the role played by LULC change as the main driver of landscape dynamics [32–35]. It has been shown that the main drivers of LULC change in Mediterranean Europe for the last two centuries have been connected with (i) agricultural and forest area trends, (ii) urban area expansion, (iii) energy transition and industrialization, (iv) land management systems, and (v) sociopolitical organization and lifestyle transformation.

First, up until the second half of the 19th century, general agricultural and forest area trends related to intensive forest clearance, farming, and grazing were reversed into so-called forest transition, with some temporal differences in each country [36–38]. In Europe, this was due to the abandonment of farmland and pastureland [39–41], which overlapped in time with national reforestation policies. In fact, the reforestation programs of the 19th and mainly 20th century, as well as the afforestation plans subsidized by the European Union (EU) in the frame of the Common Agricultural Policy (CAP) Reform, contributed significantly to reversing the deforestation trend of the previous centuries and to consolidating the current progressive processes of forestland [42,43]. In this sense, Iriarte-Goñi & Ayuda [44] have recently provided evidence of the relationship between the forest transition processes of the second half of 20th century and the increasing fire impact between 1968 and 2002 in Spain.

Second, the expansion of urbanization and new housing developments have had a strong impact on LULC change since the 1970s. In particular, urban sprawl in the most densely populated areas is creating the most challenging territories at risk, namely wildland–urban interfaces [45–47]. A third main general trend is energy transition, consisting in the substitution of biomass fuel (i.e., firewood, charcoal) by fossil fuel, in connection with the industrialization process that implied rural exodus to urban areas [48–51]. This phenomenon has led to the abandonment and quick regeneration of broad woodland areas in many Mediterranean regions during the second half of the 20th century, with obvious implications for the fire regime. In this context, the re-organization of land management systems is a forth driver of radical LULC changes at the local level, with strong multiscale implications for the fire regime. The new land management systems are (i) a reaction to the privatization of woodlands and to the introduction of the Forest Regime in the 19th century and (ii) the adaptation to rural area depopulation and to new market demands. Last but not least, the new sociopolitical organization introduced by the modern political system in the 19th century and the widespread urban lifestyle since the mid-20th century are not only a driving force of LULC changes, but they are also at the origin of a cultural shift. Paradoxically, growing technological and economic modernization has brought about a higher fire risk, which is particularly evident at the local scale.

A plethora of papers have assessed the impact of these landscape dynamics, namely LULC changes, on fire types and the fire regime in Mediterranean climate-type regions [52–57]. In the Iberian Peninsula, Pausas & Fernández-Muñoz [58] and Silva et al. [30] have considered the influence of landscape dynamics in fire regime changes at the national and regional scale, both long term (130-year time series) and medium term (1975–2013). Costafreda-Aumedes et al. [59] have also analyzed the relationship between landscape patterns and human-caused fire occurrence in Spain at a national scale between 1989 and 1993. Moreover, several studies have explored the influence of socioeconomic landscape drivers, namely LULC and demography, on fire trends in Sardinia [60,61], Greece [46] and Turkey [62]. However, the originality of this study lies in the long fire history archive that it is based on, and the long-term LULC reconstruction at the local level. Actually, this is a key issue to understanding the current fire problem in Europe where landscapes are intensively humanized as a result of a long history of use, transformation and management [34,63].

Recent LULC changes have affected traditional cultural landscapes that had evolved very slowly for centuries [64]. These changes have sharply destabilized social-ecological systems and this has triggered a stronger impact on the relatively stable landscapes. We have called this abrupt shift in fire regimes pyrotransitions in the context of nonlinear fire regime evolution [65,66].

It is clear that burning practices and wildfires have historically brought about different LULC changes in the Iberian Peninsula (i.e., conversion of natural ecosystems into farmland or pasture, with LULC changes being a proxy for human activities), but one can ask whether, and to what extent, LULC changes are modifying the parameters of the fire regime. Therefore, in this study, we are addressing two research questions in the mountain areas of Central Spain: (1) What has the real impact of fire on LULC changes been? (2) How are these LULC changes influencing the wildfire regime?

For that purpose, the main objectives of the research were to calculate and analyze the spatial and temporal pattern of LULC changes and fire history in a set of local case studies on places located in the Central Mountain System (Spain). Archival documentary sources and historical cartography were used to (1) reconstruct LULC and (2) to build a historical fire database. Three time points were established, 1890s–1930s, 1956–1957, and the 2000s, with the aim of assessing the interaction of landscape dynamics and the fire regime since the mid-19th century in a fire-prone and humanized Mediterranean territory.

2. Materials and Methods

2.1. Case Studies

We have analyzed the LULC changes of six local-scale case studies in the Central Mountain System and natural region of the Iberian Peninsula: Gata, Hurdes, Tiétar, Iruelas, El Espinar, and Sorbe (Figure 1). They are located in five different Spanish provinces (Cáceres, Salamanca, Ávila, Segovia and Guadalajara) that are also part of three different political regions (Extremadura, Castilla y León and Castilla-La Mancha).

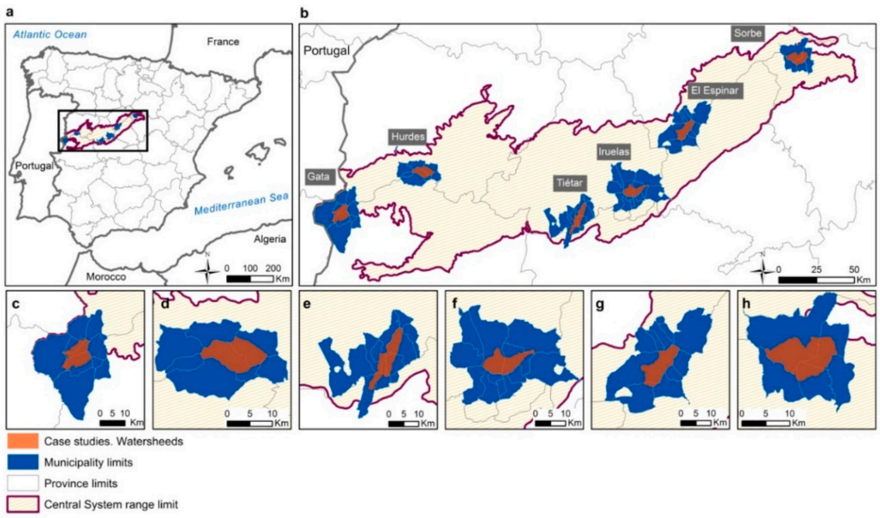


Figure 1. Location of the case studies within the natural mountain region in central Spain (**a**). Watersheds (in orange) within the municipality (NUTS5 level) limits (in blue) of each case study (**b**): Gata (**c**), Hurdes (**d**), Tiétar (**e**), Iruelas (**f**), El Espinar (**g**), and Sorbe (**h**). Province (NUTS3 level) limits in light gray. Central Mountain System limits in purple.

The six case studies are representative of the biophysical and landscape diversity of the Central Mountain System, which has been historically one of the areas most affected by wildfires in the Iberian Peninsula [8]. Actually, the six case studies have been selected in order to assess the fire-landscape interaction in different ecological and social contexts. In this regard, we have considered two selection criteria: (1) the historical evidence of fire as a land management tool and/or risk and (2) the geographical representativeness of socio-ecological systems at the regional level. We used our expert criteria and fieldwork to select the case studies with the support of Geographical Information System (GIS) techniques and by considering slope, vegetation, land tenure, forest management systems, and place names related to fire as the main analysis variables.

The selected case studies were spatially defined using as the basic spatial unit the microwatersheds drawn by the Ministry of Agriculture from the Digital elevation model (DEM) 100 m pixel size and scale 1:25,000. Each of the case studies has a total area between 8000 and 10,000 hectares and is composed of a set of microwatersheds that may differ in number. A buffer area was also defined including the municipalities around each case study for geohistorical data collection and to assess socio-ecological influencing factors.

The case studies of Gata and Hurdes share similar geoecological conditions and settlement history. In both cases, these Mediterranean mid-mountain areas (altitudes between 600 and 1600 m) on the southern slope of the Central System were colonized in the 12th century, which implied the beginning of an intense use of fire to open up areas for grazing. Unlike the Hurdes, where only small hamlets developed, the population of the Sierra de Gata (Gata range) is grouped into villages. Agricultural occupation also presents marked differences: in Gata, its much less rugged terrain allowed for vast areas of crop-growing fields (especially olive groves) [67]. In contrast, the rugged terrain of Las Hurdes continues to be mostly covered by forests [68]. The forestry predominance of this last area is reaffirmed during the 20th century with extensive reforestation processes that did not affect Gata.

Tiétar and Iruelas are located in the province of Ávila. These case studies are representative of a complex mountain terrain that stretches out on both sloping sides of the Sierra de Gredos (Gredos range). The case study of Tiétar is located on a steep south-facing slope of the Gredos range, whose highest peak is Miravelles, at 2012 m. It features a divided administrative structure and a predominantly private land tenure system, although municipal councils own most forest areas. The case study of Iruelas, however, extends over a north-facing slope in the Eastern limit of the Gredos range. It flanks the middle stretch of the Alberche River through a set of gorges and creeks among which the Iruelas gorge is outstanding. This case study is formed by only two municipalities comprising large public forests protected for nature conservation.

The El Espinar case study includes two rivers basins (Moros and Gudillos), both with steep headwaters (2197 m, Pinareja) and with a flat section downstream until their junction (1125 m). High peaks are bare and the upper slopes are covered by wide block fields, but below 1800–1900 m the valleys are densely covered by almost monospecific pine forests (*Pinus sylvestris*, L.). These pine forests are mainly public property under the Forest Regime since the 19th century. Furthermore, they were declared monte de utilidad pública (public utility forest) and became some of the first pinewoods managed by the forest engineers in Spain because of their proximity to Madrid and their reasonable state of conservation [69,70]. The main settlements in this site are San Rafael and La Estación, two traditional tourism settlements that have undergone intense demographic growth.

Finally, the Sorbe case study is located at the Sierra de Ayllón (Ayllón range), within the Province of Guadalajara (Castilla-La Mancha). Five municipalities are within the buffer area: Cantalojas, Galve de Sorbe, La Huerce, Majaelrayo, and Valverde de los Arroyos. The Sorbe area is characterized by a prevailingly sub-Mediterranean climate, with mean annual temperatures below 10 °C and mean annual rainfall above 800 mm. The Sorbe River, a headwater river of the Tagus, runs through this area of the case study, where most of the lands are public and have been historically protected by their status as "public utility forest". There is a considerable footprint of previous reforestation with *Pinus* [71]. In addition, the high mountain pastures that are spread over the area are representative of open range cattle raising for meat production. Both logging and cattle raising are two economic activities that are still ongoing in the area, despite the heavy depopulation of the last decades.

2.2. Material: Geohistorical Sources, Statistics, and Geospatial Data

2.2.1. Historical Cartography

The historical cartography used was the so-called Planimetrías (planimetries) from the Spanish National Geographic Institute. They were employed to obtain LULC data for the 1890s–1930s time point. These planimetries were made at the municipal level between 1870 and 1950 drawn at a 1:25,000 scale within a 1:50,000 precision scale resolution. However, not all Spanish municipalities are available. Planimetries contain data on LC and/or altimetry. Table 1 shows the number of available municipalities within each case study and years covered. Differences in years were found depending on each case study. This data source provides a good insight on the consequences of the progressive agricultural processes during the second half of the 19th century [72], as well as the prohibition of traditional fire practices that led to changes in fire regimes. In fact, several studies noted an increase in croplands from 16 to 18 million ha in that period at the expense of forestland [73].

Table 1. Planimetries available by case study. Number of available municipalities with LC data within each case study and years covered.

Case Study	No. of Municipalities	Years
Gata	3	1941, 1932
Hurdes	4	1903, 1904, 1907, 1931, 1945
Tiétar	2	1892, 1902
Iruelas	3	1906, 1907, 1936
El Espinar	2	1901, 1908
Sorbe	5	1895, 1896, 1897

2.2.2. Aerial Photography

Aerial photography from 1956 and 1957 was used to obtain LULC for the 1956–1957 time point. These photos came from flights over Spain carried out by the US Army Map Service between March 1956 and September 1957. The photos are black and white, have a resolution of 1-m pixel and a 1:32,000 scale. The Spanish Geographic Centre of the Ground Forces (CEGET) performed the digitization of 60,000 photos. Since 2014, this information has been available at the Spanish National Geographic Institute at no cost for institutions that belong to the Spanish National Cartographic System. Also, some Spanish regions built their own mosaics of these photographs, which were provided to us for this investigation: the Cartographic Centre of Castilla-La Mancha, the Technological and Agrarian Institute of Castilla y León and the Environment, Rural, Agrarian policies and Territory section from the government of Extremadura. This data source reflected traditional rural land management and organization of the territory before the land abandonment process [74], enclosing a specific socioeconomic period earlier than the second pyrotransition [66,72].

2.2.3. Geospatial Data

The data source used to obtain LULC covering the 2000s time point was CORINE Land Cover 2000 v.18.5, vector format (CLC2000), which belongs to Copernicus Land Cover products and is the update of the first CORINE Land Cover inventory from 1990. The CLC2000 product used ortho-corrected high-spatial resolution satellite images (Landsat-7 ETM single date, 1999) for geometrical and thematic basis mapping. In situ topographic maps, orthophotos, and ground survey data were used as ancillary information. It has 44 thematic classes and a minimum mapping unit of 25 ha. Despite the available CLC for more recent years of reference, CLC2000 was chosen because it used an image of 1999 and updated CLC90 using the same methodology. At that time, CLC2000 reflected the first consequences of the CAP launched in 1962 (Articles 38 to 44 of the Treaty on the Functioning of the European Union, [75]), i.e., intensification of certain landscapes through large-scale specialization or mono-cropping [76], forest plantations in agricultural lands or change from rainfed to irrigated farming lands. Additionally, within this time point fires were classified as 'third generation fires' [77], with high severity, large burned areas and demanding suppression. They were mainly the consequence of the low forest management of the previous ~30 years, as well as the outcome of the fire management system of that period that placed a great emphasis on the suppression of all low to medium intensity fires. Both practices have promoted a homogenous and high-density forest with vertical continuity.

2.2.4. UCM Fire History Dataset

The Research Group of Forest Geography, Policy and Socioeconomics at the Complutense University of Madrid (UCM) has created a pioneering Fire History Dataset for the inner mountain areas and the Mediterranean coastal regions of the Iberian Peninsula. This is an ongoing database organized according to the Spanish official fire statistics database (EGIF) and linked to a GIS and metadata system. It includes 62 data fields (date, location, land ownership, land cover/use, burned area, fire duration, fire cause, suppression resources, material losses, etc.).

The UCM Fire History Dataset is fed by geohistorical data collected in documentary archives. This is a valuable research resource for reconstructing long-term fire history. Due to the specific limitations of the archival sources [78–80], we cannot consider the obtained data series to be statistically valid, but they will provide relevant qualitative information about the historical fire regime.

We gathered 6591 fire records dating back to 1497 from systematic and intensive research in four types of documentary archives: (i) national, district/province, and local historical archives, (ii) forest agency archives, (iii) municipality archives, and (iv) traditional and electronic libraries. Furthermore, the historical records were georeferenced with three different spatial levels of increasing accuracy (municipality, site or area without specified boundaries, and forest or plot with accurate limits of property) depending on the accuracy of the historical source.

2.2.5. Statistical Fire Data

In Spain, fire data has been officially collected since 1968 in a national fire database (EGIF, Spanish Ministry of Agriculture, Fisheries and Food). Fire records include more than 150 fields of information related to fire such as the spatial location of the event, causes and motivations, burned area, evaluation of the damages in forest products, etc. Fire events are spatially located in a 10 × 10 km grid cell resolution, which is the minimum spatial unit used to report fire location at the national level. It was only after 1983 did the accuracy reach the municipal level, and only after 2000 were precise coordinates of the fire event recorded. In this national fire database, fire causes are classified in the following categories: lightning, negligence/accidents, deliberate, unknown, and reignited fires. For this work, the 1983 to 2013 period was analyzed because, as from 1983, the data collection was available at the municipal level.

2.3. Methodology

We have used methods of historical geography and socio-spatial systemic analysis for reconstructing and assessing the LULC change and fire history in the six selected case studies. We have explored the UCM Fire History Dataset and the statistical Spanish fire data (EGIF), looking at the number of fires by year, their location and the burned area, when available, of each event. The UCM Fire History Dataset would complement the EGIF, but the data have been obtained using different methods and they come from different sources.

As previously mentioned, technological innovation and modernization of the economy, as well as energy transition from fuelwood to fossil fuel and political transition towards a modern political system, were identified as drivers of landscape dynamics related to wildfire risk in Mediterranean Europe since the 19th century. At a national level, the rural exodus led to land abandonment [81] and a simultaneous intensification of the agricultural sector [82]. Also new industrialization and urbanization processes caused a change in lifestyles and subsequently in the territory. To reflect these processes LULC maps have been produced through an analytical process of photointerpretation and GIS following a complex procedure of ortho-rectification and classification. LULC categories used in the historical cartography have been harmonized with CLC2000 in a common hierarchical classification of LULC types, allowing for comparison in order to map the LULC changes since the late 19th century. We have followed a methodology that is, in part, similar to that used by Bazan et al. [83] and by Otero et al. [40] to study land use change in Central-Western Sicily and in the Metropolitan Region of Barcelona, respectively, for analyzing LULC changes in the six case studies selected in the Central Mountain System.

The dynamic interactions of both LULC change and the nonlinear evolution of the fire regime were approached from a local spatial scale and from a medium-term temporal scale (last century). A qualitative perspective was applied to assess their mutual related effects and the UCM Fire History Dataset was used for this purpose.

2.3.1. Historical LULC Mapping

Spatial and cartographic analyses were carried out in order to obtain the historical LULC map for the study cases. First, the planimetries from the 1890s to 1930s time points available were downloaded for each case. Then, the images were projected, overlap to current municipality limits and were subsequently adapted when they did not coincide. Afterwards, a digitization process was established followed by topological error corrections. Figure 2 shows a section of the original planimetries used for the Gata case study and the LULC polygons resulting from the digitization.

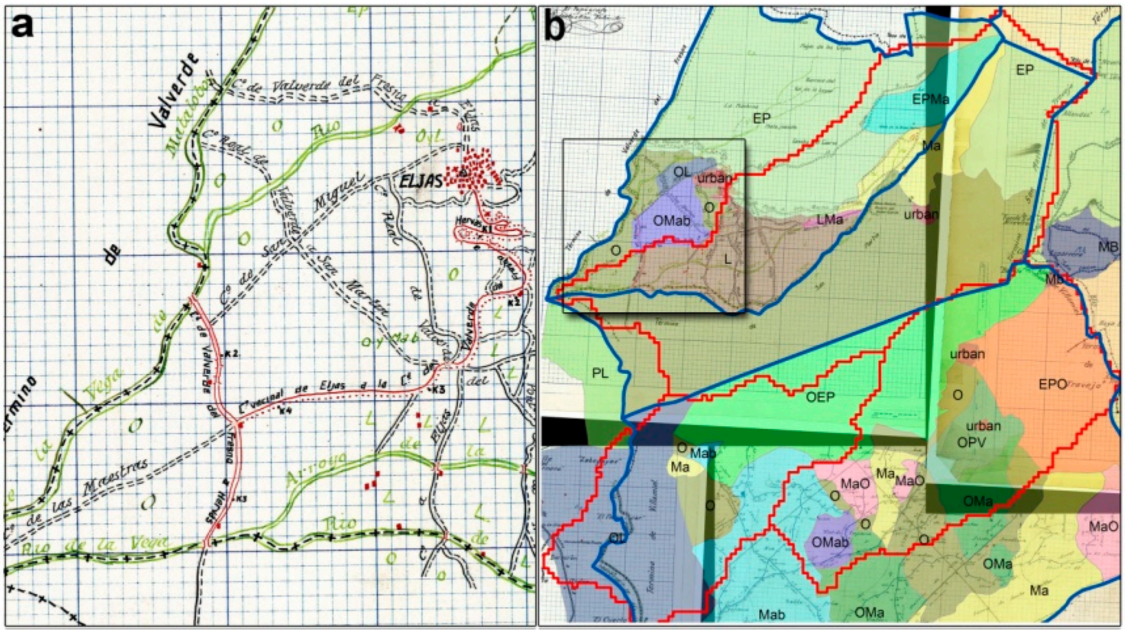


Figure 2. Original planimetry section available for the Gata case (**a**). Digitization results in Gata (red limits) after spatial composition and digitization processes (**b**). Legend: EP: grassland; L: lemon trees; Ma: forest; Mab: forest and other wooded land; MB: shrubland; O: olives; V: vineyard.

Second, aerial photographs from 1956 to 1957 that were available for the case studies were acquired. In those case studies where the georeferenced mosaic was not available or incomplete, a ground control points method was used to georeference the raw (uncorrected) aerial photographs needed. Each ground control point defined a location of two georeferencing systems: (1) the raw image coordinates and (2) the projected image used as a reference, coming from the Spanish National Plan of Aerial Ortho-photography ((PNOA). By means of associating projected coordinates within the locations, the photographs were then georeferenced in the so-called rectification process. To evaluate the positional error made, the real coordinates of the control points were compared with the calculated ones by means of the Root Mean Square Error (RMSE). Afterwards, photo interpretation was carried out in order to obtain LULC maps from each case study (Figure 3). Color, shape, texture, location, pattern, and size parameters, among others, were considered to delimit and to define each LULC polygon. Auxiliary information was also used such as the national Agricultural map from 1962, orthophoto (PNOA) and aerial photography from the 1970s. The minimum mapping unit was 1 ha.

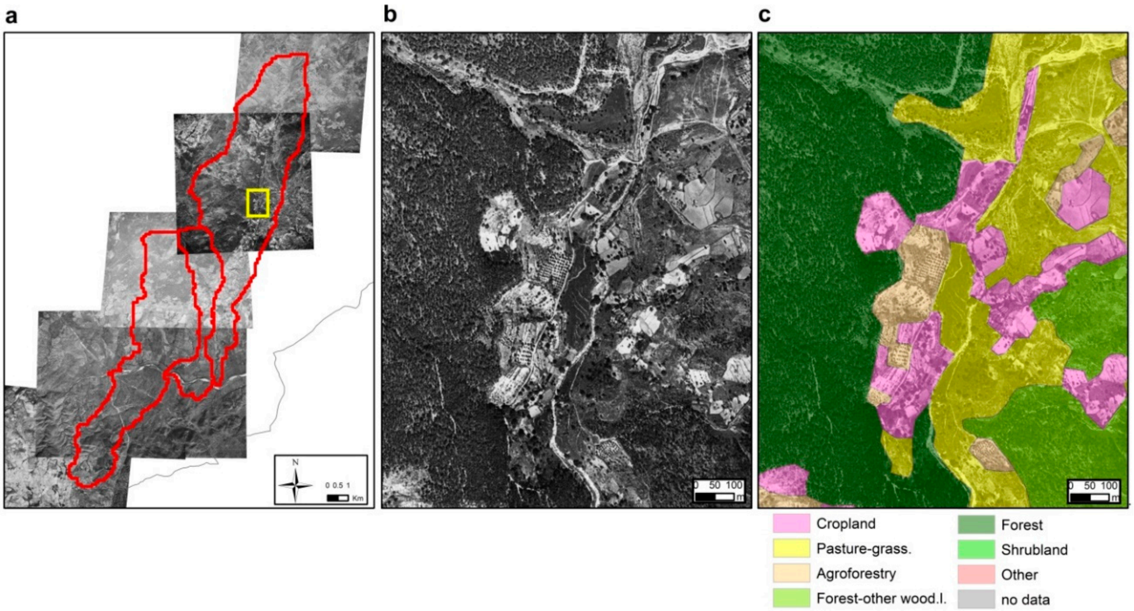


Figure 3. Aerial photography mosaic Tiétar case study: Aerial photography section (**a**). Photo interpretation results (**b**) and land use and land cover (LULC) classes obtained (**c**).

Thirdly, CLC2000 for the case studies was clipped from the Europe dataset. Then, LULC classification was defined for the elaboration of the three maps related to the considered time point in each case study. LC refers to the observed (bio) physical surface of the Earth (e.g., types of vegetation or human-made constructions), whereas LU refers to the socioeconomic purpose of the land, to which the LC is committed and the land management system is employed, e.g., residential, industrial, agricultural, forestry, and recreational purposes [84]. In this work, LU and LC were considered from an integrated approach to define a hierarchical set of LULC categories. For this purpose, drivers of landscape dynamics related to wildfire risk in Mediterranean Europe since the 19th century were first identified. Then, processes affecting the local scale were distinguished from national trends. After that, LULCs obtained for 1890s–1930s time point were classified, grouped and ranked in two levels similar to the CLC classification system [85]. Secondly, the same classification was applied for the LULC assignation after the photo-interpretation of the aerial photographs (1956–1957).

Finally, a harmonization process was applied to CLC2000 categories by using the previously defined LULC classification (Table 2). More than 130 different historical LULC classes were obtained after the digitalization of planimetries in the case studies. From these primary categories, the proposed LULC classification took into account the above-mentioned landscape dynamics drivers for defining two-level categories. The five main LULC categories in level 1 were Farmland, Seminatural grazing land, Agroforestry, Forest and woodland, and Other. In level 2, the Farmland category was subdivided into Cropland and Pasture grassland and the Forest and woodland category into Forest and other wooded land, Forest, and Shrubland. This common legend allowed a temporal and spatial comparison of the LULC change analysis to be performed from a multiscale approach.

Table 2. Harmonized classification of CLC2000 from the historical LULC-defined classes.

Level 1 (L1) Code	Description L1	Level 2 (L2) Code	Description L2	CLC2000 Classes
1	Farmland	11	Cropland	Arable land (2.1); Permanent crops (2.2); Heterogeneous agricultural areas (2.4.1, 2.4.2, 2.4.3)
		12	Pasture grassland	Pastures (2.3); Natural grassland (3.2.1)
2	Seminatural grazing land			Sparsely vegetated areas (3.3.3)
3	Agroforestry			Agro-forestry areas (2.4.4)
4	Forest and woodland	41	Forest and other wooded land	
		42	Forest	Forests (3.1); Transitional woodland shrub (3.2.4)
		43	Shrubland	Moors and heathland (3.2.2); Sclerophyllous vegetation (3.2.3)
5	Other			Artificial surfaces (1) Wetlands (4) Water bodies (5) Beaches, dunes and sand plains (3.3.1) Bare rocks (3.3.2) Burned areas (3.3.4) Glaciers and perpetual snow (3.3.5)

2.3.2. Fire History Reconstruction

Geohistorical documentary sources are a reliable basis for reconstructing fire history [86]. However, they have barely been used in scientific studies with respect to fire scars and paleo-ecological data because of their conservation limitations and difficulty to collect.

For eight years (2011–2018), we have applied research methods of Historical Geography to collect, analyze, and interpret primarily fire-related documents generated by Spanish public agencies, police forces, judicial authorities, and local communities since the end of the 15th century. These archival sources were obtained from (i) administrative documents from all the government agencies with fire use regulations and land management authority during the period, including forest agency reports, auction papers, minutes of municipal council meetings, and other documents; (ii) judicial and police documents related to court registers, legal proceedings, police reports, and fines levied since the 17th century; and (iii) newspaper archives (official journals, newspaper accounts, and historical literature).

The rich data provided by these diverse geohistorical sources and some long continuous documentary series allowed us to reconstruct the complete fire history of the Central Mountain System for the last two centuries (19th and 20th). Furthermore, we have mapped historical fire occurrence and other fire regime features like seasonality, fire types, fire causes, and other aspects.

2.3.3. Integrated Assessment of the Interactions between LULC Changes and Fire History at the Local Scale

Following the methodology of Ferrara et al. [7], we first assessed the frequency of fires at two scales: (i) the number of fire events by case study and the buffer area and (ii) the number of fire events in the Central Mountain System, considering also accuracy in the spatial location of each fire event as a sub-indicator. Fire spreading [87] was then evaluated by means of two indicators based on the burned area: (i) total burned area and (ii) total burned area by size of the fire—large fire (>100 ha), medium (50–100ha), and small fire (<50 ha). Temporal trends of both fire frequency and fire spreading were analyzed.

Second, LULC changes between time points (1890s–1930s and 1956–1957; 1956–1957 and the 2000s) were calculated, grouping them into five types: (1) Agriculture and pasture abandonment; (2) Progressive processes of forestland; (3) Regressive processes of forestland; (4) Stability of LULC; and (5) Other changes. The spatially located fire events were then overlaid on the previously defined LULC change type. Finally, comparisons and visual analyses of the fire frequency and fire spreading by LULC changes were carried out by case study, buffer area and time point. We also explored the spatial distribution of historical fires in relation to LULC changes by applying the chi-squared test [57] to quantify the impacts of LULC changes on wildfires and vice versa.

3. Results

3.1. Historical Land Use/Land Cover Reconstruction

Figure 4 shows the LULC historical maps (1890s–1930s, 1956–1957, and the 2000s) obtained in the six local case studies.

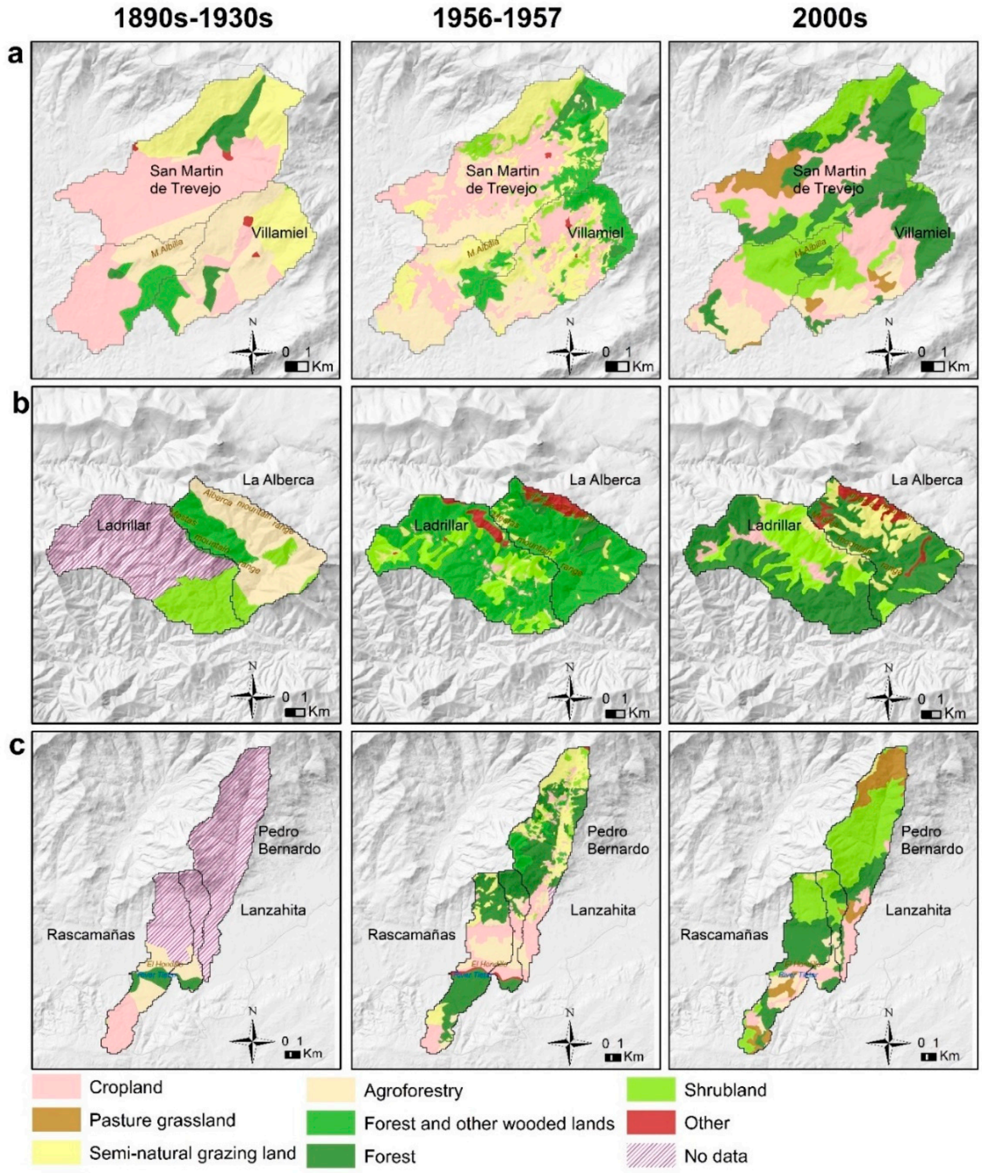


Figure 4. *Cont.*

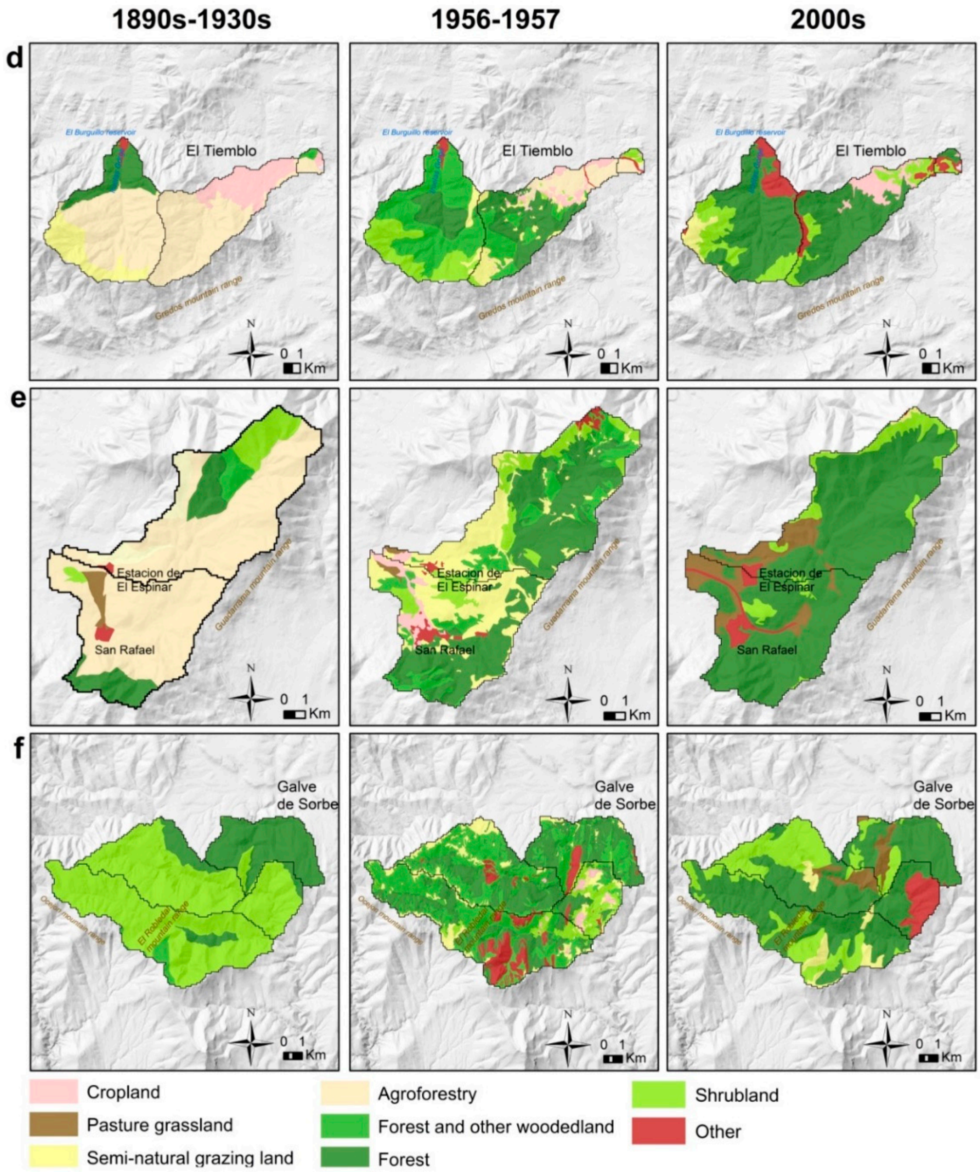


Figure 4. Maps of historical LULC: Gata (**a**), Hurdes (**b**), Tiétar (**c**), Iruelas (**d**), El Espinar (**e**), and Sorbe (**f**).

The spatial location and distribution of LULC classes between case studies and by time point were noticeable as seen in Figure 4. In Gata (Figure 4a) the dominant classes of cropland and agroforestry were spatially located in the West and central area of the site, while seminatural grazing lands were located mainly up North and forest and woodland showed a patch-pattern for the 1890s–1930s time point. This LULC distribution evolved towards a fragmentation of cropland and agroforestry areas in the mid-20th century while seminatural areas became forests. In Hurdes (Figure 4b), data from the 1890s–1930s time point is unfortunately incomplete, but agroforestry areas covered the East part of this site at the end of the 19th century. The reforestations of the mid-20th century changed the landscape, but a remarkable progression of shrublands and seminatural grazing land was registered in the central area of this case study in the 2000s. In Tiétar (Figure 4c), between 1890 and 1930, only the South had known data, where cropland and agroforestry were the dominant LULC classes and forestland was limited to the banks of the River Tiétar. From 1956 to 1957, the northern areas were covered by forest and seminatural grazing land; the central areas were covered by cropland and agroforestry while forests and croplands were distributed in the southern areas. In the 2000s, northern forest areas became seminatural grazing land and pastures, the central areas became forests, and the south became forests, seminatural grazing lands and agroforestry. Overall, this is the most complex and changeable LULC evolution of all of the case studies. Iruelas (Figure 4d) was mainly an agroforestry site in between 1890 and 1930, and forestland was reduced to a small patch in the North. Nevertheless, from 1956 to 1957, most agroforestry areas became forests, and in the 2000s, cropland became agroforestry. In this case study there was also a regression in the 2000s, as forest areas to the West became seminatural grazing lands and some eastern agroforestry areas became cropland. El Espinar (Figure 4e) was also a dominant agroforestry site between 1890 and 1930, although some polygons had an ambiguous classification as woodlands and seminatural grazing areas in the historical planimetries, as was also the case in the Iruelas case study. Forest progression from the eastern and southern mountain areas was significant from 1956 to 1957 and forestlands are definitively predominant in the 2000s, with the exception of urban areas and a few pasture and grasslands. Finally, Sorbe (Figure 4f) was a forest site between 1890 and 1930 and, in the mid-20th century, it showed some patches of seminatural grazing land. In the 2000s, this case study maintained its forested landscape character with a diversified mosaic of shrubland, forest and other woodland classes.

After the reconstruction of LULC historical maps, Figure 5 illustrates the percentage of LULC categories in the analyzed time points (1890s–1930s, 1956–1957, and the 2000s) and its variation by case study.

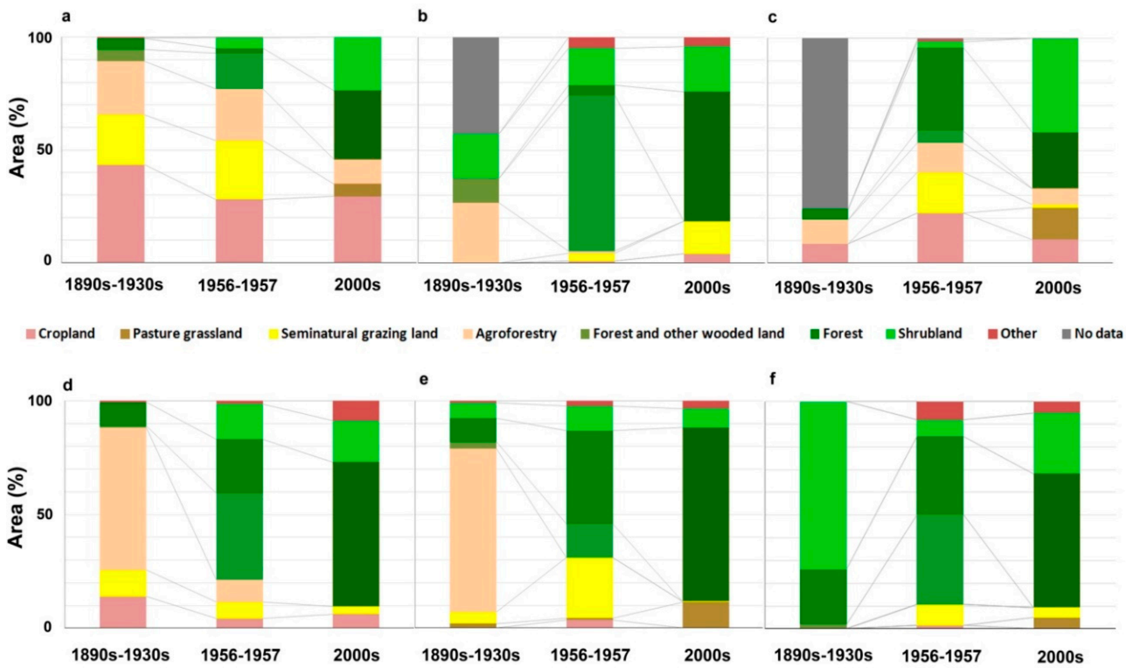


Figure 5. LULC variation in the study cases in the analyzed time points (1890s–1930s, 1956–1957, and the 2000s): Gata (**a**), Hurdes (**b**), Tiétar (**c**), Iruelas (**d**), El Espinar (**e**), and Sorbe (**f**).

In general, the Gata case study (a) is the most agricultural site. By time point, between 1890 and 1930, the agroforestry LULC type dominated in Iruelas (d) and El Espinar (e). In the Gata case study, (a) cropland and seminatural grazing lands covered the largest areas. On the contrary, the Sorbe case study (f) was forestland. In the second time point (1956–1957), agroforestry dominated sites mostly became forest and seminatural grazing LULC, while cropland decreased in Gata and seminatural grazing land increased in Sorbe. In the 2000s, the general trend was forest and other woodland progression, except in Hurdes and Iruelas where instead, seminatural grazing lands, and agroforestry percentages increased, respectively.

By case study, in Gata (a) croplands covered ~40% between 1890 and 1930, but its area slightly decreased in the second period and in the 2000s, forestland classes represented ~50% of the total area. In Hurdes (b), the general reforestation of the mid-20th century changed the landscape of the 1890s to 1930s, but the seminatural grazing land recovered a remarkable ~20% in the 2000s. In Tiétar (c), there is not a clear LULC spatial pattern change, but from 1956 to 1957 ~50% of the site was covered by forest and ~50% by agroforestry, seminatural grazing land, and cropland, while in the 2000s forestland covered ~70%, and the pasture grassland category is introduced with ~15% of the total area percentage. Iruelas (d) is a prototypical example of evolution from an agroforestry and farmland landscape to a protected forest area within a century. Between 1890 and 1930, the agroforestry class was >60% of the area, even if woodlands and seminatural grazing lands had a notable representation in this wide LULC category. From 1956 to 1957, forest and shrubland classes dominated almost 80% of the site area, and forest density had significantly increased in the 2000s. In El Espinar (e), more than 70% of the total area was also covered by agroforestry between 1890 and 1930, according to the interpretation of historical primary sources. However, this LULC class was replaced in the following periods by different forestland and seminatural grazing categories, and in the 2000s, forestland covered more than 70% of the total area in this case study. In Sorbe (f), more than 70% of the total area was covered by shrubland between 1890 and 1930, but this percentage was drastically reduced in 1956–1957 due to forest progression. It should also be noted that the increase of the category 'Other' in this site is mainly due to the differences in primary source scales and can be seen in Figure 4b–f, stressing the importance of spatial data. Thus, in 1956–57, it refers mainly to rocky areas, and in the 2000s, it corresponds to a burned area caused by a large wildfire on 14 August 1991.

Beyond the presented landscape character and dynamics of LULC categories, it is also important to evaluate landscape dynamics by assessing the whole rate of stability or change in each case study. Table 3 shows the percentage of total area where LULC changed between the analyzed time points as well as the area where LULC categories remained the same, indicating stability.

Table 3. Percentage of total LULC changes and stability in the study cases between analyzed time points. Largest percentages in bold.

	(1890–1930)–(1956–1957)		**(1956–1957)–(the 2000s)**	
Case Study	**Changes (%)**	**Stability (%)**	**Changes (%)**	**Stability (%)**
Gata	62.11	**37.89**	55.43	**44.56**
Hurdes	87.21	12.79	**94.79**	5.21
Tiétar	**90.19**	9.81	77.07	22.92
Iruelas	**93.32**	6.68	73.03	26.96
El Espinar	85.96	14.04	53.49	**46.51**
Sorbe	79.89	**20.11**	77.23	22.77

Gata and Sorbe, at both ends of the Central Mountain System, presented larger stability values in the first interval between 1890–1930 and 1956–1957 (in bold). On the contrary, larger changes (lower stability percentages) can be found in the Tiétar and Iruelas sites, in the Province of Ávila. Nevertheless, we should notice that the change or stability rates between 1890–1930 and 1956–1957 in Tiétar and Hurdes are less important because of the relative data gap in the first time point. In the second interval from 1956–1957 to 2000s, Gata and El Espinar were the most stable sites while in Hurdes more than 90% of the total area underwent changes.

3.2. *Fire History Reconstruction*

According to the UCM Fire History Dataset (1497–2013), Table 4 shows (i) the total number of historical fire records, (ii) total burned area (ha), (iii) burned area by fire size (large fire, >100 ha; medium size fire, 50–100 ha; small fire, <50 ha) when data is available, and (iv) the percentage of records with the best level of accuracy, meaning those located within the boundaries of a given plot of land or property, by case study and its buffer area and also for the whole Central Mountain System natural region (see Figure 1).

Table 4. Number of historical fire records, total burned area, burned area by fire size, percentage of accurate records by case study and its buffer area. Source: UCM Fire History Dataset, 1497–2013.

Case Studies	N Fire Records	Burned Area (ha)	Burned Area—Large Fires (>100 ha)	Burned Area—Medium Size Fires (50–100 ha)	Burned Area—Small Fires (<50 ha)	% Records with Best Accuracy Level
Gata	137	1923.0	1662.5	77.3	183.2	5.1
Hurdes	54	354.4	-	210.0	144.4	66.7
Tiétar	339	10,254.5	9517.0	310.0	427.5	25.7
Iruelas	479	14,940.1	13879.7	484.3	576.1	35.1
El Espinar	292	3185.6	2274.5	501.0	410.1	52.4
Sorbe	53	4442.9	4305.0	-	137.9	64.2
Central Mountain System	2159	47291.7	44381.8	1382.4	1527.4	64.4

The highest number of historical fire records (~22% of the total fire records of the Central Mountain System) and largest total burned area (~32%) is registered in the Iruelas case study followed by Tiétar. Large wildfires were widely distributed across the Central Mountain System, while the sum of small wildfires contributed to an outstanding burned area (>400 ha) in both the Tiétar and Iruelas sites. Regarding the level of accuracy of fire records provided by documentary sources, there are wide disparities between case studies. At the Hurdes and Sorbe sites, more than 60% of fire ignitions were accurately recorded, but the percentage of accurate records is very low in Gata, which is a notable constraint for analyzing the relationship between LULC change and fire regime evolution.

The evolution of fire frequency and its resulting burned area has not been linear in either time (Figure 6) or in space (Figure 7). At the regional scale, two abrupt fire regime shifts, called pyrotransitions, have been documented in the Central Mountain System. First, we have identified a sudden increase in fire ignitions and related burned area in the late 1800s and early 1900s [65,88]. Then, a second abrupt shift around the 1950s, similar to other regions, has also been recorded [89–91]

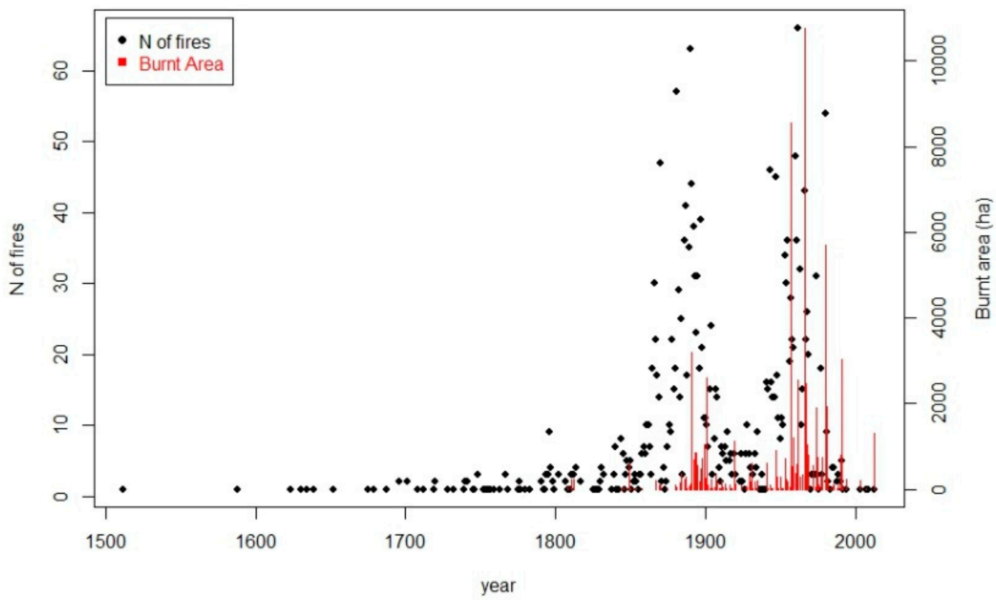


Figure 6. Number of historical fire records and burned area (ha) by year in the Central Mountain System natural region. Source: UCM Fire History Dataset.

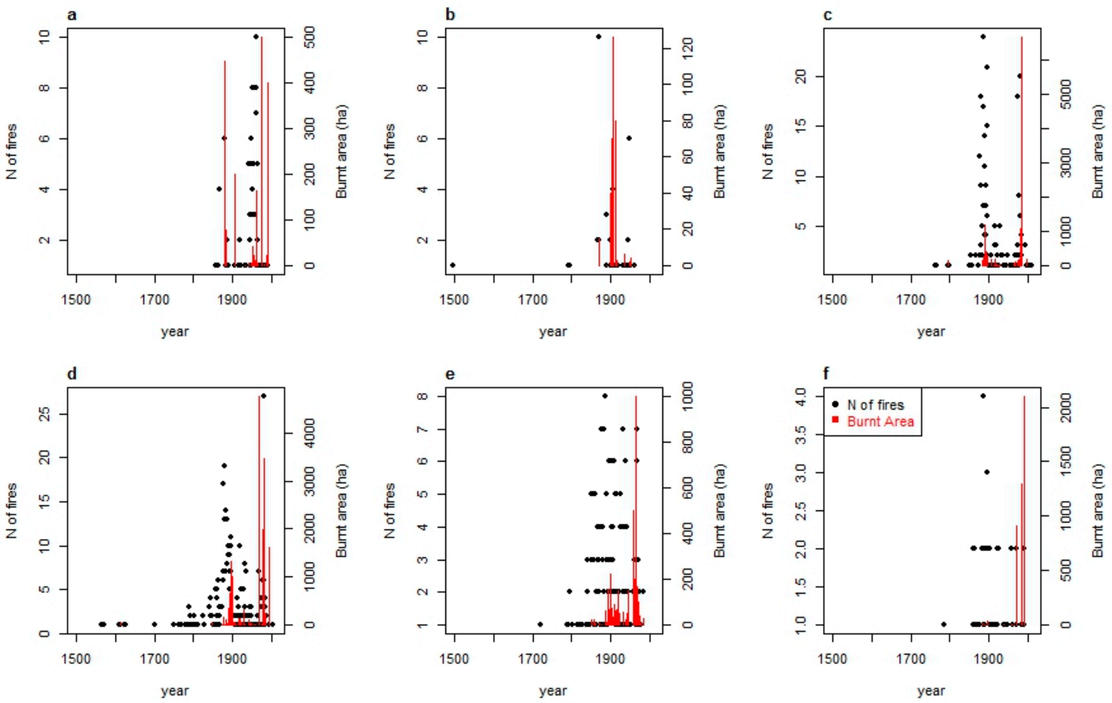


Figure 7. Number of fire records and burned area (ha) by year for each case study: Gata (**a**), Hurdes (**b**), Tiétar (**c**), Iruelas (**d**), El Espinar (**e**), and Sorbe (**f**). Source: UCM Fire History Dataset.

Nevertheless, the sociopolitical, socioeconomic and socio-ecological system destabilization and related pyrotransitions happened at different rhythms and with specific features in each site (Figure 7), depending on the contextual factors at the local level [66,74,92]. Although all case studies have registered an abrupt shift in the fire regime in the 1900s, this shift was sharper and particularly evident concerning increased burned area in Hurdes and Gata. In Tiétar and Iruelas, however, it was mainly related to fire ignitions according to the regional pattern. Moreover, this first type of pyrotransition was less evident in El Espinar and Sorbe compared to the second one, which was the most abrupt shift in all the sites except Hurdes where it has not even occurred.

Table 5 shows the exploratory analysis of Fire Statistics Data for the 1983 to 2013 period and Figures 8 and 9 illustrate the number of statistical fire records and burned area by year in the Central Mountain System natural region and in each case study, respectively. The main feature of this statistical period is a high interannual variability without an identified trend of fire ignitions and burned area, and the increasing instability of the fire regime. Even if 1985 was an extreme year at the regional and national level, and other critical episodes were recorded in 1986, 1989, 1991, and 2003, the evolution of burned area in this mountain region is completely variable over time and between the different case studies.

Table 5. Number of fire records, total burned area and burned area by fire size. Source: Spanish Fire Statistics Data, 1983–2013.

Case Studies	N Fire Records	Burned Area (ha)	Burned Area—Large Fires (>100 ha)	Burned Area—Medium Fires (50–100 ha)	Burned Area—Small Fires (<50 ha)
Gata	2099	24,492.7	16,572.2	2717.9	5202.6
Hurdes	711	15,672.5	13,105.1	652.1	1915.3
Tiétar	1083	13,921.98	10,263.28	1488.75	2169.95
Iruelas	1134	12,611.5	10,753.9	345.0	1512.6
El Espinar	556	1786.4	536.8	395.7	853.9
Sorbe	86	2987.8	2793.3	0.0	194.5
Central Mountain System	25,365	280,696.7	197,651.9	24,082.2	58,962.6

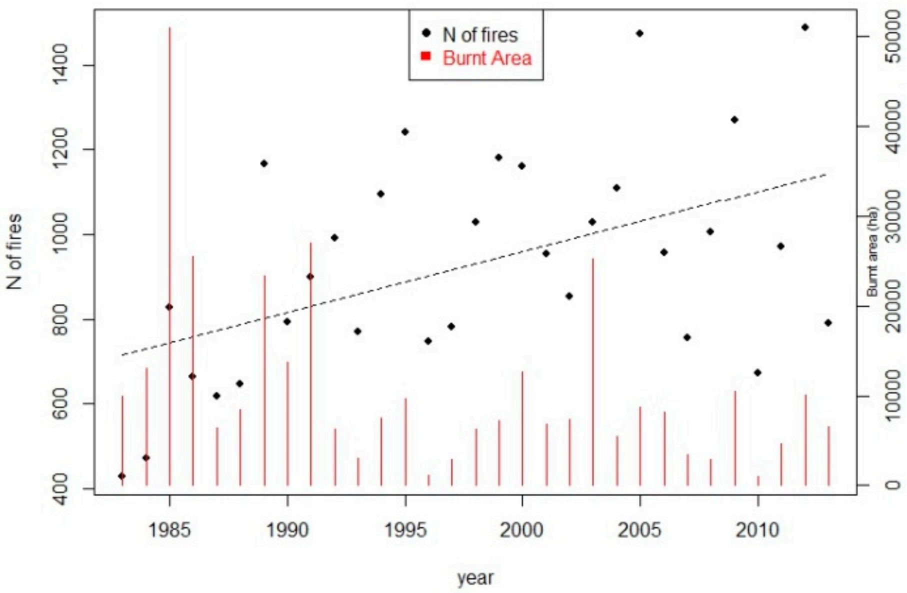


Figure 8. Number of fire records and burned area (ha) by year in the Central Mountain System natural region. Fitted trend dashed line for the number of fires vs. the year. Source: Fire Statistics Database.

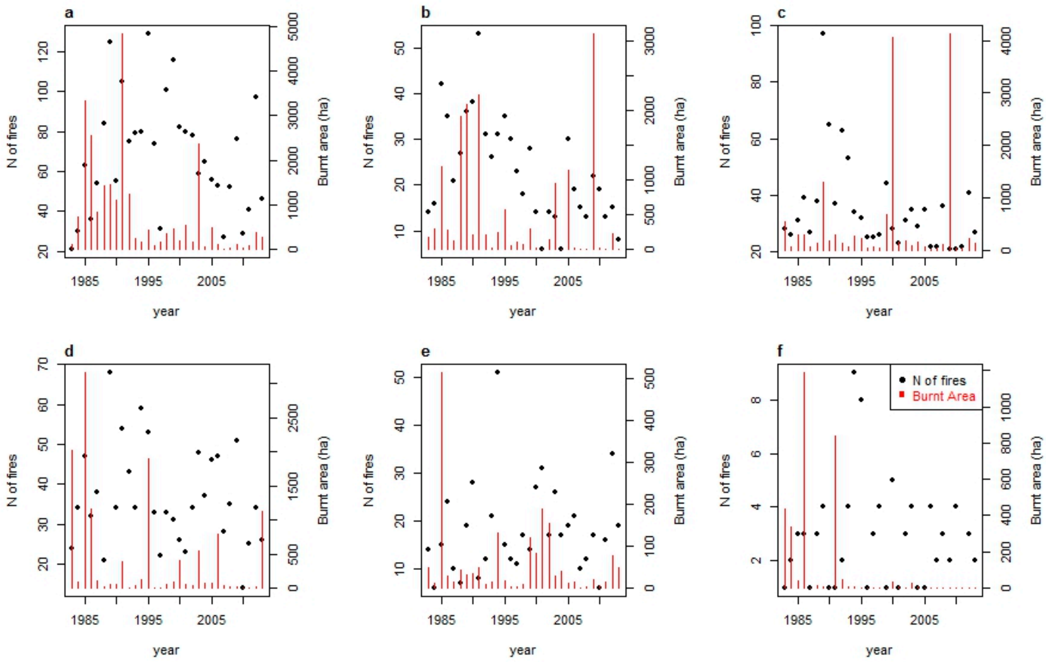


Figure 9. Number of fire records and burned area (ha) by year for each case study: Gata (**a**), Hurdes (**b**), Tiétar (**c**), Iruelas (**d**), El Espinar (**e**), and Sorbe (**f**). Source: Fire Statistical Database.

Concerning the number of fire records, we note an increasing trend of fire ignitions at the regional scale since the 1990s, but clear trend patterns cannot be found at the local level. Gata and Hurdes recorded the highest figures of burned area for the 1983 to 2013 period (Table 5). Both sites together represented ~8% of the total burned area in the Central System. Furthermore, fire ignitions were significantly higher in Gata compared with other case studies. Thus, in the statistical period sites from Cáceres province (Gata and Hurdes) replaced Ávila province sites (Iruelas and Tiétar) as the main fire-prone areas in the Central Mountain System.

As regards fire size patterns, there are also wide disparities between case studies. Large fires represent the highest values of burned area in all sites except in El Espinar, where wildfires were mostly small fires (<50 ha). Besides, it is important to note that medium-size fires represent the lowest burned area figures in all sites, reinforcing the idea that the general pattern during this statistical period is either small fires related to a rapid and effective fire suppression response, or large fires when extreme weather overwhelms the suppression system [5,52].

3.3. Spatiotemporal Patterns of Land Use/Land Cover Changes and Fire Occurrence

LULC changes since the late 1800s have been related to socioeconomic factors and lifestyle in Mediterranean European countries [7]. The reconstruction of the series of historical LULC maps provides accurate information of the LULC changes occurring in different places of the Spanish Central Mountain System, enabling assessment of the influence of these contextual factors on the fire regime in each interval at the local scale.

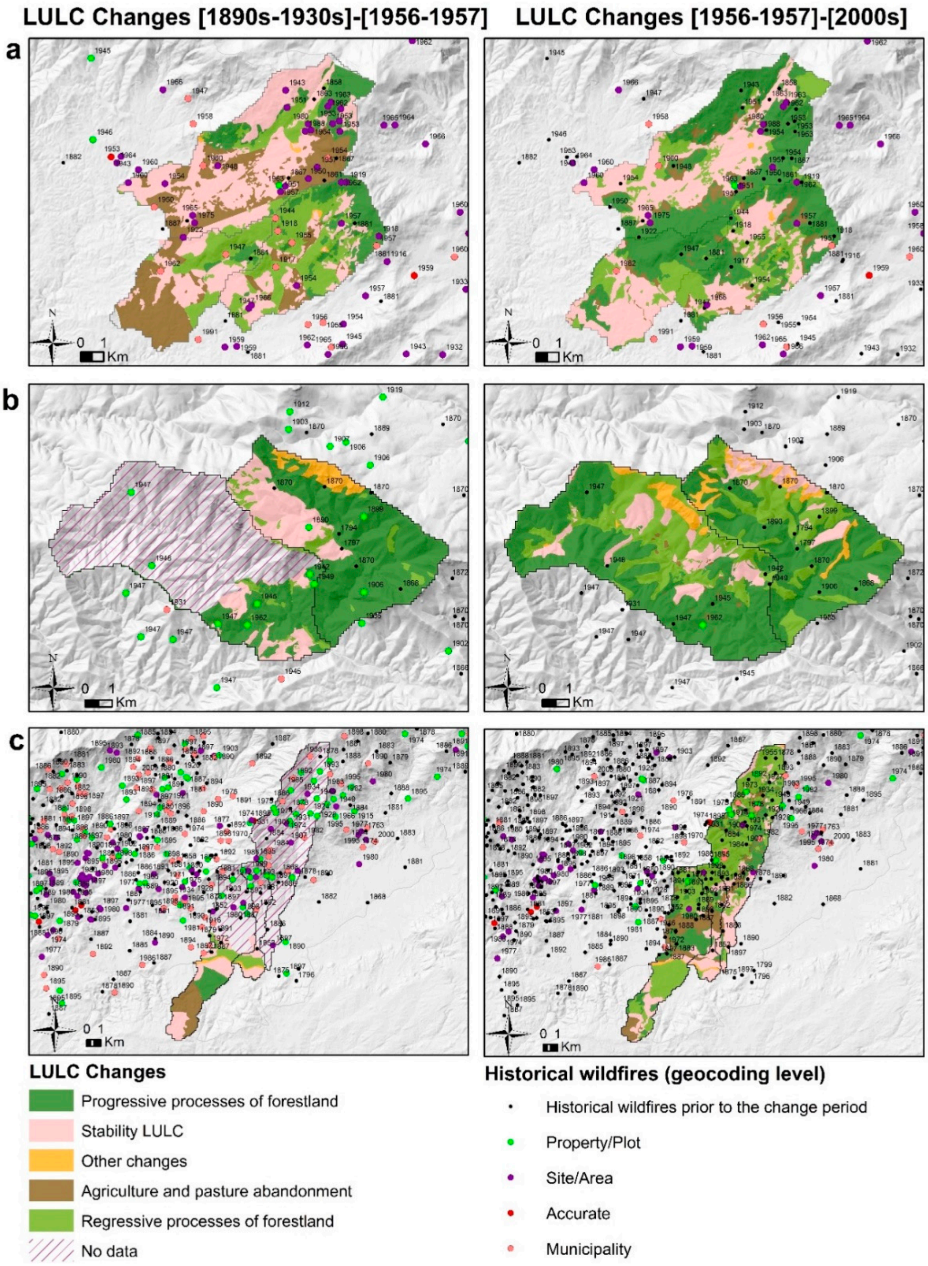
According to the successional theory, we have recognized a general trend of forest regeneration after agriculture and pasture abandonment and different stages of forest succession in abandoned farmland and woodlands resulting in an increased height and density of biomass [40,64]. Nevertheless, the revegetation processes related to land abandonment have not always triggered ecosystem restoration. Agricultural decline and pasture grassland abandonment have sometimes undergone progressive processes of ecosystem recovery (e.g., conversion of seminatural grazing land into forests and other woodlands), while, at other times, they have determined regressive processes of ecological degradation (e.g., conversion of agroforestry into seminatural grazing land). Moreover, the driving forces of landscape dynamics have not caused the same successional trends of LULC changes in all case studies. Furthermore, these processes have shown important variations in time and rates depending on the history of land use at the local scale.

We have classified the LULC change trends observed in the two studied intervals (first, between the 1890–1930 and 1956–1957 time points; and second, between the 1956–1957 and the 2000s time points) in five categories: (1) Agriculture and pasture abandonment; (2) Progressive processes of forestland; (3) Regressive processes of forestland; (4) Stability of LULC; and (5) Other changes. Figure 10 illustrates these LULC changes and the related historical fire occurrence in all case studies, indicating the year and accuracy of each fire record.

In Gata (Figure 10a), some areas remained stable in both intervals, mostly in the central and southern areas of the case study. Besides a high rate of LULC stability, the main LULC changes in the first period were related to the agriculture and pasture abandonment and to regressive processes of forestland, while the second period was dominated by the progressive processes of forestland. However, Hurdes (Figure 10b) showed a decreasing LULC stability rate and opposite forestland trends: progressive processes of forestland dominated in the first period because of reforestations in the mid-20th century, but regressive processes of forestland spread after 1956–1957. In the Tiétar case study (Figure 10c), agriculture and pasture abandonment and regressive processes of forestland were the dominant LULC trends in both temporal intervals, with the lowest rate of landscape stability in the South-East area. In Iruelas (Figure 10d) and El Espinar (Figure 10e), we observed a dominant trend of progressive processes of forestland in the first half of the 20th century, then an increasing LULC stability in the second period. Finally, a similar LULC change trend occurred in the Sorbe case study (Figure 10f), although the regressive processes of forestland were evident in the second interval.

Summing up, in the first LULC change period (1890–1930 to 1956–1957), Gata and Tiétar case studies mostly experienced agricultural abandonment while progressive processes of forestland dominated in the other case studies. In the second interval (1956–1957 to 2000s), LULC trends were more varied and a high landscape stability was registered in all case studies except in Tiétar and Hurdes where regression processes of forestland increased. Besides, the LULC changes registered in each case study vary from one period to another. Therefore, there is no general spatial or temporal pattern of LULC change in the Central Mountain System during the 20th century. On the contrary, landscape dynamics have been strongly dependent on local history and social-ecological character.

Historical fire records within and prior to each LULC change interval were also located in Figure 10 at the geocoding level shown in the primary sources: (i) randomly in the mentioned place name site/area, (ii) within the boundaries of a plot or property, (iii) at the accurate ignition point, and (iv) randomly within the municipality limits. Considering the more accurate fire records, we can observe the coincidence of fire ignitions with different types of LULC change, either agriculture and pasture abandonment or progressive or regressive processes of forestland, and a lower percentage of fire records in LULC stable areas. For instance, in the Gata case study, most fire records were geocoded at the site/area level in the farmland abandonment or progressive processes of forestland areas in both LULC change periods. Wildfire occurrence in the Tiétar case study during the second 20th century was also concentrated in LULC change areas, but regressive processes of forestland were registered. We have recorded a similar fire occurrence in stable areas, but only in Iruelas and El Espinar, during the second and first half of the 20th century, respectively.



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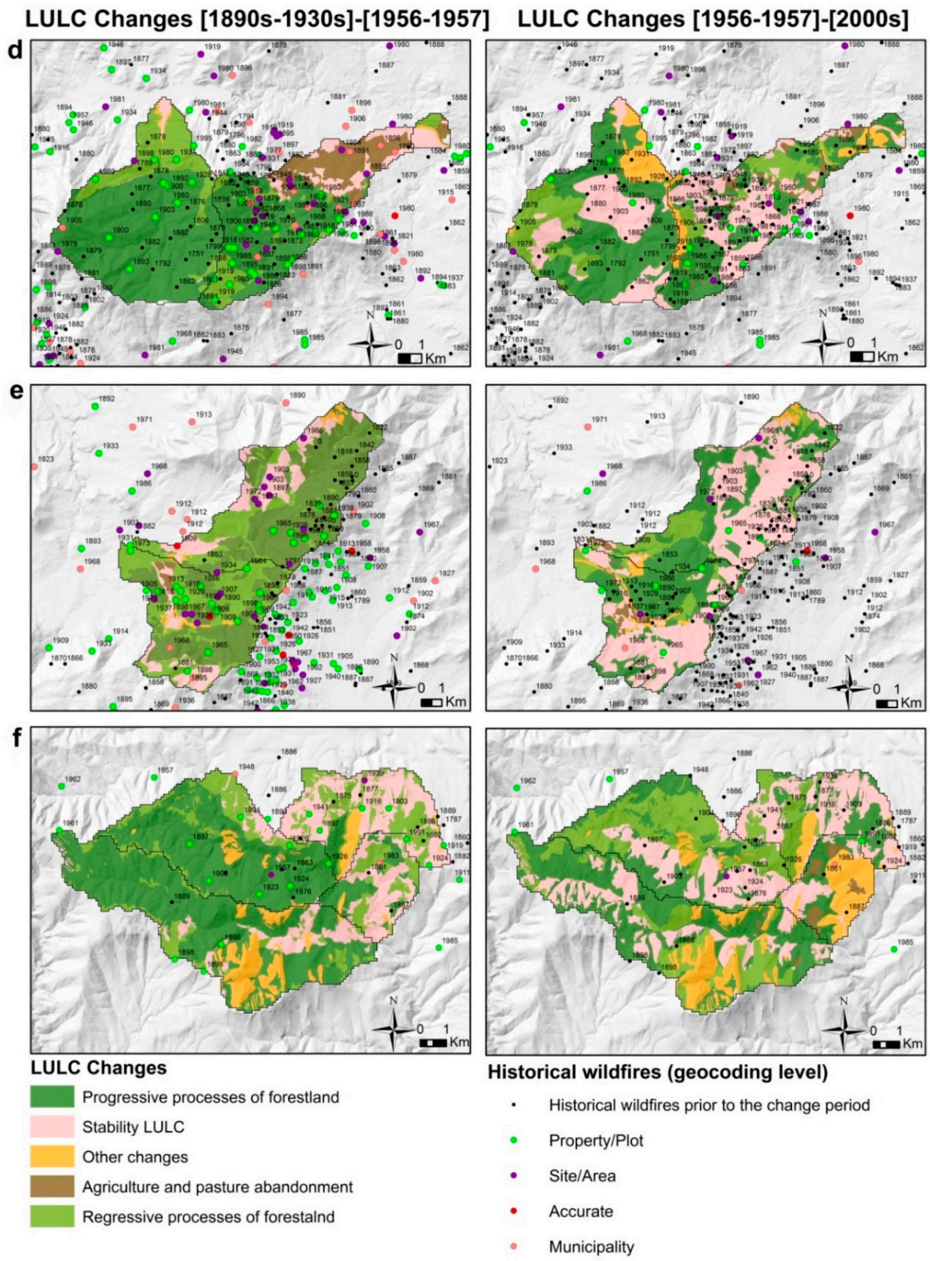

Figure 10. Maps of LULC changes between time points: 1890–1930 and 1956–1957, and 1956–1957 and 2000s, and historical fire records within and prior the interval: Gata (**a**), Hurdes (**b**), Tiétar (**c**), Iruelas (**d**), El Espinar (**e**), and Sorbe (**f**).

We also explored the spatial distribution of historical fire records in relation to the LULC change types using the chi-squared test with the expected fire occurrence (Tables 6 and 7). We found that most of the fire records and the highest amounts of burned area happened during the LULC change of progressive processes of forestland during the first transition period (1890–1930 to 1956–1957). Furthermore, most of the fire records took place during times of stability and progressive processes of forestland as well during the second LULC change period (1956–1957 to 2000s). However, higher amounts of burned area were found in the LULC change of regressive processes of forest lands in this second interval. Chi-squared test results indicate that the number of fires did not significantly differ in any of the case studies from what could be expected based on each type of LULC change in both of the intervals considered here between the time points of 1890s–1930 and 1956–1957, and 1956–1957 and 2000s.

Table 6. LULC change area and %, number of fires, and burned area (ha, %) by LULC changes between the time points 1890–1930 and 1956–1957 in each case study. Chi-squared test results for the number of fires.

	LULC Change																													
	Stability					**Agriculture and Pasture Abandonment**					**Progressive Processes of Forest Land**					**Regressive Processes of Forest Land**					**Other Changes**					**No Data**				
Study Case	**Area (ha)**	**Area (%)**	**N Fires**	**BA (ha)**	**BA (%)**	**Area (ha)**	**Area (%)**	**N Fires**	**BA (ha)**	**BA (%)**	**Area (ha)**	**Area (%)**	**N Fires**	**BA (ha)**	**BA (%)**	**Area (ha)**	**Area (%)**	**N Fires**	**BA (ha)**	**BA (%)**	**Area (ha)**	**Area (%)**	**N Fires**	**BA (ha)**	**BA (%)**	**Area (ha)**	**Area (%)**	**N Fires**	**BA (ha)**	**BA (%)**
Gata	3257.1	37.9	6	31.2	51.8	2071.8	24.1	7	24.0	39.9	1304.3	15.2	7	no data	no data	1933.0	22.5	6	5.0	8.3	29.4	0.3	0	0.0	0.0	0.0	0.0	0	0.0	0.0
Hurdes	903.1	12.8	2	0.02	0.1	0.0	0.0	0	0.0	0.0	2686.1	38.0	4	20.3	99.9	270.5	3.8	1	no data	no data	187.9	2.7	0	0.0	0.0	3013.5	42.7	2	no data	no data
Iruelas	502.8	7.2	1	no data	no data	747.6	10.8	6	299.0	17.5	4903.0	70.6	24	1409.8	82.3	747.6	10.8	6	4.4	0.3	43.8	0.6	0	0.0	0.0	0.0	0.0	0	0.0	0.0
Tietar	758.3	9.8	1	no data	no data	440.6	5.7	0	0.0	0.0	309.4	4.0	0	0.0	0.0	282.0	3.7	0	0	0.0	67.1	0.9	0	0.0	0.0	5872.6	75.9	31	538.2	100.0
Espinar	1173.5	14.9	5	9.3	4.4	79.3	1.0	0	0.0	0.0	4164.1	53.0	15	122.1	58.0	2290.4	29.2	10	79.0	37.6	150.3	1.9	1	no data	no data	0.0	0.0	0	0.0	0.0
Sorbe	1738.7	20.1	4	4.0	27.9	0.0	0.0	0	0.0	0.0	4556.5	52.7	7	6.0	41.9	1649.9	19.1	4	4.3	30.1	699.8	8.1	0	0.0	0.0	0.0	0.0	0	0.0	0.0

Chi-squared test for the number of fires in the different LULC change results were Gata (χ^2 = 12, df = 10, p = 0.2851); Hurdes (χ^2 = 18, df = 15, p = 0.2627); Iruelas (χ^2 = 18, df = 15, p = 0.2627); Tietar (χ^2 = 12, df = 10, p = 0.2851); Espinar (χ^2 = 24, df = 20, p = 0.2424); Sorbe (χ^2 = 12, df = 10, p = 0.2851).

Table 7. LULC change area and %, number of fires, and burned area (ha, %) by LULC changes between the time points 1956–1957 and 2000s in each case study. Chi-squared test results for the number of fires.

	LULC Change																													
Study Case	**Stability**					**Agriculture and Pasture Abandonment**					**Progressive Processes of Forest Land**					**Regressive Processes of Forest Land**					**Other Changes**					**No Data**				
Study Case	**Area (ha)**	**Area (%)**	**N Fires**	**BA (ha)**	**BA (%)**	**Area (ha)**	**Area (%)**	**N Fires**	**BA (ha)**	**BA (%)**	**Area (ha)**	**Area (%)**	**N Fires**	**BA (ha)**	**BA (%)**	**Area (ha)**	**Area (%)**	**N Fires**	**BA (ha)**	**BA (%)**	**Area (ha)**	**Area (%)**	**N Fires**	**BA (ha)**	**BA (%)**	**Area (ha)**	**Area (%)**	**N Fires**	**BA (ha)**	**BA (%)**
Gata	2851.9	49.3	5	1.5	4.5	460.4	7.9	3	1.6	4.6	3836.1	66.3	6	8.7	25.7	1471.7	25.4	2	22.0	65.3	16.8	0.3	0	0.0	0.0	0.0	0.0	0	0.0	0.0
Hurdes	775.6	12.3	0	0.0	0.0	28.3	0.5	0	0.0	0.0	3921.2	62.4	1	0.01	100.0	1995.0	31.7	0	0.0	0.0	341.7	5.4	0	0.0	0.0	0.0	0.0	0	0.0	0.0
Iruelas	2368.5	45.6	9	1201.0	27.5	180.6	3.5	0	0.0	0.0	3318.9	63.9	7	1190.0	27.3	1086.5	20.9	1	1975.0	45.2	598.7	11.5	1	no data	no data	0.0	0.0	0	0.0	0.0
Tietar	1526.2	24.6	1	40.0	12.4	1052.8	16.9	0	0.0	0.0	1475.8	23.9	3	no data	no data	3552.3	57.2	12	281.5	87.6	77.2	1.2	0	0.0	0.0	46.5	0.6	0	0.0	0.0
Espinar	3672.2	87.1	6	50.0	20.2	128.6	3.1	0	0.0	0.0	3020.4	71.6	6	197.5	79.8	815.2	19.3	0	0.0	0.0	248.5	5.9	0	0.0	0.0	0.0	0.0	0	0.0	0.0
Sorbe	2444.3	39.4	2	501.0	27.8	119.4	1.9	0	0.0	0.0	2873.3	46.3	0	0.0	0.0	2087.6	33.7	0	0.0	0.0	1120.3	18.1	1	1300.0	72.2	0.0	0.0	0	0.0	0.0

Chi-squared test for the number of fires in the different LULC change results were Gata (χ^2 = 24, df = 20, p = 0.2424); Hurdes (χ^2 = 6, df = 5, p = 0.3062); Iruelas (χ^2 = 18, df = 15, p = 0.2627); Tietar (χ^2 = 18, df = 15, p = 0.2627); Espinar (χ^2 = 6, df = 5, p = 0.3062); Sorbe (χ^2 = 12, df = 10, p = 0.2851).

4. Discussion

Aiming to answer the two research questions addressed in this study: (1) What has the real impact of fire on LULC changes been? (2) How are these LULC changes influencing the wildfire regime? The results obtained in the six case studies have stressed the importance of the local scale to assess the interaction of landscape dynamics and fire regime variation.

Regarding the fire trends found, two abrupt fire regime shifts (pyrotransitions) happened in the Central Mountain System [66]. A sudden increase in fire ignitions occurred in the late 1800s and early 1900s. This first change-point is linked to the sociopolitical crisis at the end of the 19th century. Actually, the first pyrotransition is the result of the destabilization of land tenure and the forest management system due to reinforcement of the modern political system in Spain. New forest management criteria and conflicts between the forest agency and local communities related to the socioeconomic reorganization of rural areas affected the fire regime. After the socio-ecological and socioeconomic restructuring of rural areas in the first half of the 20th century, a second sharp peak was documented in the 1950s. In this case, the pyrotransition was triggered by energy transition, the industrialization process and the generalization of the urban lifestyle. This socioeconomic crisis entailed rural exodus and loss of rural culture, land abandonment and uncontrolled biomass accumulation. Therefore, the fire regime change was mainly related to fire propagation with an abrupt increase in burned area which evolved through the fire generations model [5,8,52] to the generalization of large fires in the 90s and finally to the current megafires.

As seen, the two pyrotransitions happened at different rates in each case study depending on the specific social-ecological system destabilization conditions at the local scale. In fact, those fire regime shifts revealed differences in diverse contextual aspects such as land cover, land management, demographic trends, and social conflicts. For instance, as we can see in Figure 11, contrasting demographic variations have taken place since 1877, with El Espinar growing and the Sorbe area shrinking. Furthermore, the general depopulation trend of the second half of the 20th century took place at different times and speeds in each case study, except in El Espinar. Furthermore, the first pyrotransition occurred at the same time as the regional patterns in Gata and Hurdes, where agricultural abandonment and processes of forestland dominated, respectively. However, the second regional pyrotransition in the 1950s did not occur in the Hurdes case study as it was sharply impacted by reforestation measures. In other studies done in a Mediterranean landscape (Valencia province) [58] they found an increase in fire size and frequency of large fires after the 1970s, coincident with the rural depopulation and fuel availability also linked to drier conditions.

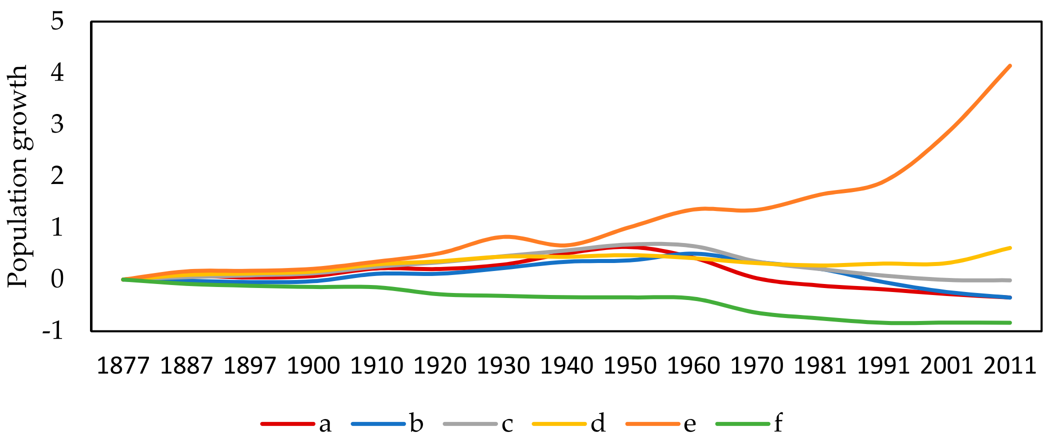

Figure 11. Demographic variation between 1877 and 2011: Gata (**a**), Hurdes (**b**), Tiétar (**c**), Iruelas (**d**), El Espinar (**e**), and Sorbe (**f**). Value 0 corresponds to the first population census figure: Gata: 15,697; Hurdes: 6051; Tiétar: 12,677; Iruelas: 18,975; El Espinar: 8738; Sorbe: 2947. Source: Statistics Spain, INEbase.

Although LULC changes have been the main influencing factor of fire occurrence at the local level, we have not found any evident correspondence between fire records and regressive processes of ecological degradation in Central Spain mountain areas. On the contrary, most LULC progressive changes occurred after historical fires in the studied temporal intervals: 1890–1930 to 1956–1957, and 1956–1957 to the 2000s. For instance, in the case of Iruelas, they took place during the first half of the 20th century and, in Gata and Hurdes, during the second half of the century. We have also documented stable LULC after fire occurrences in the El Espinar and Sorbe case studies. The only exception is the Tiétar case where regressive processes of forestland (Figure 12b) coincide with historical fire records, but this coincidence seems related to the high fire frequency and recurrence of wildfires.

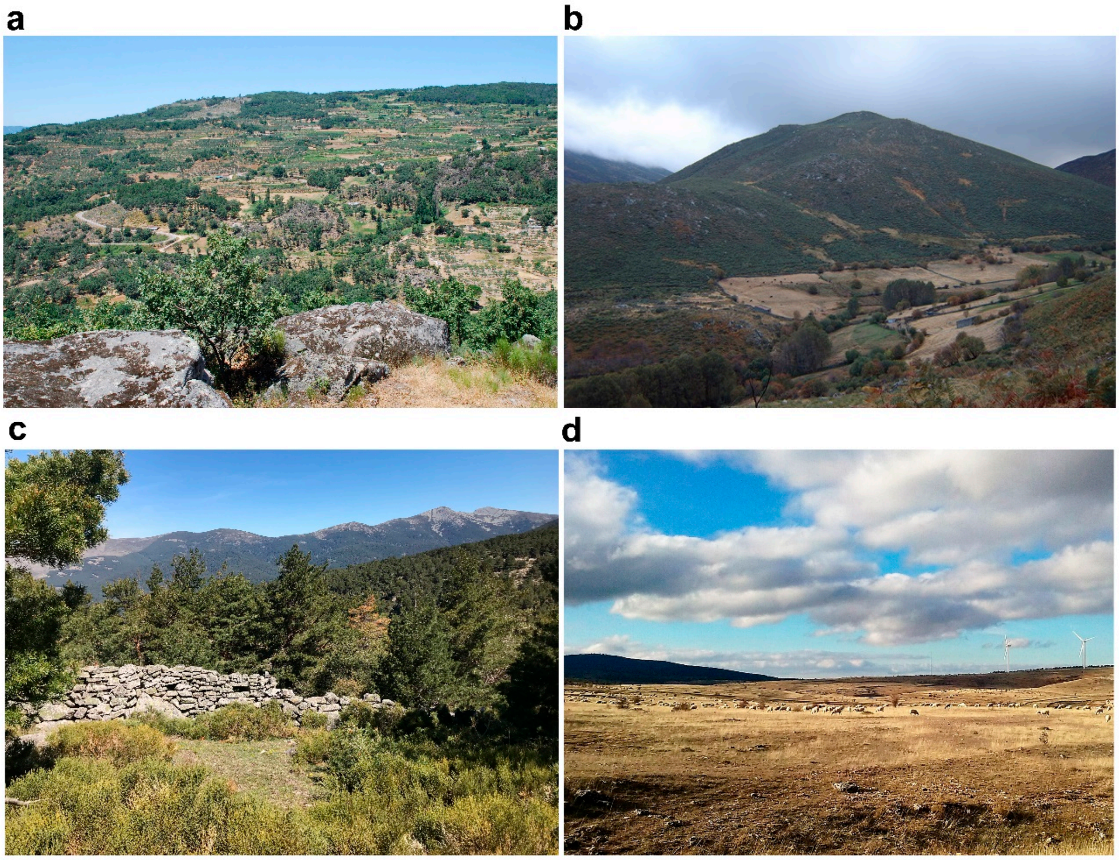

Figure 12. Photos of case studies: Agroforestry landscape in Gata (**a**). Regressive processes of forestland in Tietar (**b**). Stable forestland in El Espinar (**c**). Seminatural grazing land in Sorbe (**d**).

The results obtained seem to indicate that land management systems are the driver of LULC change that has the greatest influence on landscape resilience to wildfires in Central Spain. Moreover, landscape resilience to wildfires largely depends on the historical fire regime in terms of fire frequency and size types. In fact, the stationary landscapes in terms of LULC are less fire-prone areas because of human presence and fuel control through land management. Besides, large fire frequency occurred in LULC change areas with progressive processes of forestlands due to forest management abandonment. However, the largest burned areas occurred in regressive processes of forestland areas, where forest have been substituted by more flammable vegetation types such as shrublands [93] (Figure 12b).

Paradoxically, afforestation and land abandonment processes in Hurdes have dismantled the socioeconomic system and led to landscape homogenization but have not increased fire risk. Furthermore, this is the case study with a highest rate of LULC change in the second half of the 20th century, but the only one where the second pyrotransition was not identified. The most relevant difference that could explain this refers to fire history, because fire records and burned area were significantly lower in this case study. In fact, Hurdes and Sorbe are the two case studies with a lowest number of historical fires and a higher accuracy of fire records, both of them traditionally being the major grazing economies of the study areas.

Iruelas is the case study with a highest record of historical fires and burned area. It also registered the highest LULC change rate in the first half of the 20th century. Nevertheless, the forest protection, human presence, and a remarkable LULC stability trend in the second half of the century have reduced the fire risk and increased its fire landscape resilience.

The most fire-resilient landscapes correspond to the forestland dominant case studies such as El Espinar and Sorbe with a continuous land management system and high LULC stability in the second half of the 20th century (Figure 12c, d). Gata was also an example of fire landscape resilience because of its fire history, agroforestry character and also high LULC stability, but recent land management abandonment has destabilized this fire-adapted landscape (Figure 12a).

5. Conclusions

Local-scale studies help us to understand complex socio-ecological systems under fire risk [7,64]. The six case studies selected in the Central Mountain System (Spain) to study the coupling relationship between LULC changes and fire regime variation have proved that local scale bio-physical and socioeconomic factors define a wide diversity of spatial and temporal situations within the regional context of landscape dynamics.

LULC changes have been mainly related to agriculture and pasture abandonment and progressive processes of forestland during the 20th century in Central Spain. However, wildfire occurrence was only related to landscape instability instead of stable LULC areas. In fact, historical fires were mainly recorded in all types of LULC change category, either in farmland or forestland areas with progressive or regressive ecological processes.

Fire occurrence did not have a direct impact on LULC change during the 20th century, unless high rates of fire frequency were recorded, as was the case in the Tiétar case study. However, historical LULC changes have been a driving force of fire occurrence and a determining factor of fire regime shifts in Central Spain since the mid-19th century. Ultimately, a comparison of fire regime parameters in relation to LULC changes at the local-scale enables a clearer understanding of the fire–landscape interaction to support land management decision-making to mitigate fire risk.

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