RESEARCH ARTICLE

Quantification of the spatial resilience of the Spanish rural landscape to fire occurrence analysed using the SISPARES network of plots

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Abstract

Context   In Spain, fire is a tool used for management in rural landscapes but also wildfires can play a disruptive socio-ecological role. Therefore, its spatial structure analysis and spatial resilience quantification to wildfire is useful for territorial planning and management.

Objectives   We evaluate the relationship between the spatial structure of Spanish rural landscapes with the historical wildfire frequency. We develop and calculate indices of spatial resilience to wildfires and large wildfires.

Methods   We followed a stratified sampling based on the biogeoclimatic classes grouping by ecoregions. We calculated landscape metrics with Fragstats and collected wildfires occurrence from a national wildfire database. Spatial resilience was estimated with a self-elaborated index, using wildfires data and landscape structure subjected to a MANOVA and to a linear regression model.

Results   The Northwest region suffered more wildfires and large wildfires than the other ecoregions. The differences in frequency of large wildfires were small and low in. Some landscape metrics were positively related to wildfire frequency (forest plantations and scrublands) and other negatively ("dehesas" and crops). Spatial resilience to wildfires and large wildfires was lower in the Northwest area but for large wildfires were also low in the Mediterranean Littoral and Central region.

Conclusions   The relationship between the frequency of the two types of wildfires and landscape structure determines differences in spatial resilience indices. Large wildfires are positively related to shrubland abundance, whereas small wildfires are positively related to heterogeneous agricultural areas. Therefore, spatial resilience indices could be used as early warning tools to prevent wildfires.

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Introduction

The spatial structure of a landscape is the result of human activities and natural processes. In the

Mediterranean Region, the rural landscape has long been modified by human influence and, particularly, fire, together with grazing and firewood extraction, were tools used in the clearing and removal of plant biomass (Costafreda-Aumedes et al. 2013). In the European Union (EU), rural cultural landscapes (i.e. spaces shaped by primary activities—agriculture, livestock farming and forestry use) are considered as part of their common heritage and there are, on a continental scale, different initiatives focused on their conservation and development by implementing measures to ensure their viability (or the persistence of certain characteristics) (Acebes et al. 2016; Rey-Benayas et al. 2019). A cultural landscape constitutes a socio-ecological system in which nature (ecosystems) and culture (humans) co-evolve. The separation between nature and culture, or between people and place, is an operational tool in many cases, but any artificial division of the constituent elements of a system without a holistic unifying framework can obstruct genuine understanding of complex systems such as cultural landscapes. From an ecological point of view, these rural cultural landscapes are complex adaptive systems, shaped and maintained by agrarian activities on the territory and characterised by populations with an empirically acquired rural culture (Berkes et al. 2000; Rescia et al. 2012). Basically, rural societies optimised (adjusted) the use of space by taking advantage of the natural supply of resources (matter) and free energy flows provided by the geomorpho-physical (spatial) properties of the territory and, in turn, developed certain types of tools and established constructions specific to the different systems of use they applied.

Globally, and particularly in the EU, the rural population has been declining since 1950 (Carbonaro et al. 2016). In fact, regions where there has been a significant proportion of population loss over a period greater than or equal to one generation are referred to as "shrinking regions" (Grasland et al. 2008). Specifically, 47% of the total population was concentrated in rural areas in 1950 and is projected to fall to 19.5% by 2030 (UN 2019). The decline of the rural population has led to its rapid ageing and masculinization (demographic imbalance based on a deficit of women in proportion to that which should exist naturally, that is, a deficit of the female population in relation to the demographic structure of the territories, Camarero et al. 2009), the depopulation of rural areas and

the cessation of agricultural activities (MAPA 2011, 2020). The lack of measures to reverse the current conditions in rural areas will accentuate, on the one hand, the abandonment of traditional agricultural systems, mainly extensive, and, on the other hand, will give continuity to the intensification of the farms of those farmers and stockbreeders who do not abandon their activity. Agricultural intensification implies an increase in skilled labour, the application of new agricultural techniques, the use of pesticides and fertilisers and the use of heavy machinery.

In Spain, the decline of the rural population, from 43% in the 1960s to 19% in 2021 (World Bank 2022), has also led to both rural abandonment and agricultural intensification. Rural abandonment had, and is having, different environmental (as well as social) effects, the most obvious result of which is a natural recovery of abandoned land. While this recovery can lead to an increase in biodiversity in the long term, it also leads to a decrease in agro-biodiversity and increases the risk, frequency and intensity of fires due to the accumulation of plant biomass (fuel) and, as a practically irreversible effect, generates a loss of rural culture associated with traditional land use systems (e.g. "dehesas", extensive steppe crops or mountain livestock farming, see Lasanta et al. 2005; Rey-Benayas et al. 2007; Rescia et al. 2012). At the same time, the application of the different intensification inputs, in addition to achieving higher production, has important environmental consequences such as diffuse pollution, soil erosion and degradation, the spread of pests and fires due to landscape standardisation, simplification and degradation of habitats and loss of species/habitats (Loepfe et al. 2010; Vanwalleghem et al. 2011). Therefore, the abandonment of agricultural activities and the displacement of the population together with the intensification of farms are affecting the rural environment in such a way that the tight and millennial process of integration between the population and the territory could be approaching a critical or tipping point (Scheffer et al. 2001; Rescia et al. 2012; Taylor and Rising 2021).

In rural areas, fire regimes are highly dependent on human activities, and it is therefore relevant to analyse the relationship between land use changes generated by abandonment and intensification and the occurrence and spread of wildfires, especially in rural cultural landscapes characteristic of the Mediterranean and Spain (Lloret et al. 2004, Aquilué et al.

2020). In these territories with secularly humanised landscapes, where anthropogenic ignitions far outweigh natural ignitions, changing human activities in rural areas are modifying historical fire regimes. As Rodrigues et al. (2016) assert, most of the human drivers of wildfires have a temporal dimension, well beyond the occurrence of change, and it is for this reason that we need a historical-temporal analytical perspective coupled with the spatial dimension. Our study will specifically address the spatial dimension related to the frequency of fire ignition in Spain but will relate it to historical records of these fire events.

In general terms, there is evidence that the socio-economic changes of the last decades, synthesized in the abandonment and intensification of the rural environment, led to changes in the spatial structure of the landscape (Uematsu et al. 2010; Aune et al. 2018; González-Avila et al. 2018), both in the composition and configuration of land use and in land management. These changes generated a greater spatial homogeneity (Rescia et al. 1994, 1997), resulting in a different response capacity of the rural landscape to fire, being more vulnerable depending on the spatial structure resulting from the changes (Ortega et al. 2012a). In previous studies, the spatial resilience of rural landscapes to other types of disturbances, such as insect pests in agricultural landscapes (Rescia and Ortega 2018; Ortega et al. 2020), was analysed also using a composite index of indicators of the composition and spatial configuration of the farming system context under consideration. However, to our knowledge, there are no studies quantifying the spatial resilience of rural landscapes to fire. The development of such indicators is particularly useful for environmental management and, in particular, a spatial resilience index can be a vital tool for the control of fires and large fires, which are increasingly widespread in the Mediterranean area and in Spain (Rodrigues et al. 2016). Spatial resilience has been defined as the way in which the spatial structure of a system influences its ability to withstand a perturbation (Cumming 2011). In the context of landscapes, spatial resilience to disturbance is determined largely by the composition, configuration, and functions of patches within landscapes. An understanding of ecological, general, and spatial resilience provides the ability to develop resilience-based frameworks and decision support tools to inform management policies, goals, and actions (Chambers et al. 2019). From this point

of view, in order to analyse the spatial resilience of a landscape to a disturbance such as a wildfire, it is necessary to know how many fires have occurred in that landscape structure. If there have been many fires, it is because the landscape structure is susceptible to wildfires and therefore its spatial resilience to wildfire will be low. However, if there have been few wildfires, it is because the landscape structure is not very susceptible, i.e. it will have a higher spatial resilience. The number of fires is important for spatial resilience because in areas with more fires the time to recover landscape structure probably it will be large than in areas with scarce fires.

In this study, using data on the composition and spatial configuration of Spanish rural landscapes integrated in the Spanish Rural Landscape Monitoring System (SISPARES), we evaluated, on the one hand, the relationship between the current spatial structure of these landscapes with the historical frequency of two types of fires (small and large in terms of surface area) and, on the other hand, the spatial resilience of rural landscapes to the two types of fires in the different biogeoclimatic regions of Spain considered in SISPARES. To determine the spatial resilience of landscapes to fires, we developed two indices that consider the landscape metrics as positive or negative indicators of the capacity of spatial resilience of two types of fire. Specifically, the objectives of this study were the following: to analyse the frequency of wildfires over a 42-year period in relation to the spatial structures of rural landscapes at the scale of biogeoclimatic regions (a) and to develop and calculate quantitative indices of spatial resilience of rural landscapes taking into account the total frequency of wildfires (small and large) (b) and with the frequency of large wildfires (c).

Materials and methods

Study area

The study was carried out in rural landscapes of Spain, within the Iberian Peninsula and the Balearic Islands (about 497,000 km^2 in total), using 206 plots of 4×4 km randomly located following a stratified sampling design based on the biogeoclimatic classification, CLATERES, developed by Elena-Rosselló et al. (1997). This classification is a multifactorial

ecological territorial model of Spain that facilitates the inventory, evaluation, monitoring and research of plant resources. CLATERES was designed for getting estimates at a national scale of a wide variety of ecological features and used a classification approach adapted from the country survey land classification system (Bunce et al. 1996). The CLATERES classes consist in 215 ecological zones with similar biotic and abiotic factors such as topography, vegetation, and climate (only 206 were used in this study, Canary Islands was excluded). These classes were derived from a TWISPAN analysis that allowed their grouping into 7 ecoregions in Iberian Peninsula and the Balearic Islands (Elena-Rosselló et al. 1997) (Fig. 1). The potential for integration of environmental data from regional stratifications such as CLATERES into a European monitoring framework has been demonstrated (Ortega et al. 2012b).

Characterization of the landscape structure

The rural landscape plots are part of SISPARES which is a Landscape Monitoring System designed and developed for Spanish landscapes (Gómez-Sanz et al. 2014). SISPARES data are derived from aerial photo interpretation and tessellation of Land Use and Cover Types in the sampling units, in five survey dates: 1956, 1984, 1998, 2008 and 2018. These dates were determined according to the availability of aerial images for the whole country.

In this study we used the most recent survey, landscape spatial structure data have been recorded in all the study area in the year 2018 by means of satellite images SENTINEL of European Space Agency. The sampling intensity, taking into account the plot size and the total extension of the study area, is about 1/146. The minimum size of mapped plots is 1 ha. However, where delimited patches (of

Fig. 1 Map 206 plots of 4×4 km randomly located following a stratified sampling design based on the biogeoclimatic classification, CLATERES, developed by Elena-Rosselló et al. (1997). Their grouping into 7 ecoregions in Iberian Peninsula and the Balearic Islands is indicated. Ecoregions are called **1** Galaico-Cantábrica, **2** Duriense, **3** Catalano—Aragonesa, **4** Litoral Mediterránea, **5** Extremadura, **6** Ibérico—Manchega and **7** Bética

at least 1 ha) comprise multiple portions of different land uses (each less than 1 ha) that are intermixed at such a fine scale, these patches are classified as heterogeneous agricultural areas (composed mainly of crops, with significant areas of natural vegetation).

The structure of the landscapes was analyzed using landscape metrics based on the following: (i) The area covered by the following eight major land use types: forests (F), forest plantations (FP), riparian woodlands (RW), shrublands (S), pastures (P), agro-forestry areas called ''dehesas'' (D), crops (C), heterogeneous agricultural areas (HET), rocks (R), water bodies (W), and artificial surfaces (urban and industrial areas, U). These land use types correspond to level 3 of land cover CORINE classification (EEA 1995); and (ii) Landscape metrics describing the composition and configuration of landscapes that were selected taking into account previous studies in these sampling plots that determined their vulnerability to fire frequency (Ortega et. 2012a) (Table 1). For the calculation of the landscape metrics, the land uses/covers shapes from 2018 SISPARES survey were digitally rasterised to a pixel size of 5 m. Analyses were performed with Fragstats 4.0 (McGarigal, et al. 2012).

Wildfires data

For characterizing the spatiotemporal patterns of wildfire occurrence, we used the national fire database (EGIF, https://www.miteco.gob.es/es/biodiversidad/servicios/banco-datos-naturaleza/informacion-disponible/incendios-forestales.aspx), the most complete collection of wildfire data in Spain, which is compiled by the "Area de Defensa Contra Incendios Forestales" of the Spanish Ministry of Environment. EGIF records daily wildfire data since 1974 in 10 km×10 km UTM square resolution, including their causes, which are summarized yearly. Such a database allows for a combined analysis of wildfire occurrence and landscape structure (as provided by the SISPARES framework described earlier) from 1974 to 2015 (the most recent data on fires have not yet been published in the official database). In order to spatially link the SISPARES and wildfire databases, we overlaid the 10 km×10 km UTM grid of wildfire occurrence with the CLATERES classes. This process was facilitated because the CLATERES classes were designed with 2×2 km resolution and a UTM projection as for the wildfire data. For each CLATERES class (each corresponding to a continuous region with homogeneous biogeoclimatic conditions and represented by one SISPARES plot) we calculated 42 descriptors of wildfire occurrence (one per year) from the UTM 10 km×10 km squares intersecting that class: the average number of ignitions and the average number of large wildfires (> 500 ha) in that period was matching to the landscape metrics of plot calculated from 2018 survey of SISPARES.

Table 1 Metrics used to describe landscape composition (Relative total area of different land use and land cover; SDI) and configuration (MPS and RD) in the 16 km² SISPARES plots across Spanish rural landscapes

Landscape metrics	Description
"Dehesa" area	Total area of "Dehesa" land use in the landscape
Crops area	Total area of crops land use in the landscape
Forest area	Total area of forest land use in the landscape
Heterogeneous agricultural area	Total area of heterogeneous agricultural land use in the landscape
Shrubs area	Total area of shrubs land use in the landscape
Riparian woodlands	Total area of riparian woodlands land use in the landscape
Forest plantation	Total area of forest plantation land use in the landscape
Shannon diversity index (SDI)*	Shannon index calculated from the proportions of total area covered by each land use and land cover type in the landscape. This index considers richness (variety) and evenness (relative abundance) of land-use patches
Mean patch size (MPS)*	Average size of patches in the landscape
Road density (RD)	Total road length per unit area in the landscape

*Further details on the rest of the metrics can be found in McGarigal et al. (2012)

Data analyses

The average number of ignitions and the average number of large wildfires were subjected to a MANOVA analysis to determine the biogeoclimatic environment in which fires occur. For this analysis, the CLATERES biogeoclimatic class grouping by ecoregion was used as a classification factor. The landscape metrics of the 206 4×4 km plots were also subjected to a MANOVA analysis with the same classification factor, the ecoregion.

To find a significant relationship between landscape structure and wildfire frequency that allows us to calculate the spatial resilience index to wildfires, the landscape metrics of 206 plot of 2018 SISPARES survey were subjected to backward linear regression models using the summation of number of ignitions in 42 years as dependent variable. The same type of analyses was used to find the relationship between landscape structure and frequency of large wildfires, using the summation of number of large wildfires in 42 years as dependent variable.

Spatial resilience index (SRI)

To determine the spatial resilience of rural landscapes to the wildfires, we developed two indices that consider landscape metrics significantly related to fire frequency as positive or negative indicators of the spatial resilience of the landscape to wildfire. The selection of positive and negative variables (indicators) was made on the basis of their suppressive (detrimental) or promotive (beneficial) character for the abundance of wildfire and large wildfires.

A min–max normalization was used for the data of the indicators that compose the index, which thus maintained the differences in the actual measured magnitudes. In this way, it was possible to interpret and unify the scale for all indicators (values between 1 and 10; multiplying by 10 each normalized variable in (1) and (2), see equations below). When the SRI of the landscape is maximum (high values of the positive components of the equations and minimum values of the negative ones), the resilience of the landscape to fire is maximum (it is not prone to fire). Conversely, this index would reach a minimum value when the indicators benefiting resilience have a minimum value and the indicators negatively affecting resilience (subtraction components in equations) have

a maximum value. In this case, the spatial resilience of the landscape will be minimal and will have a high susceptibility to fire.
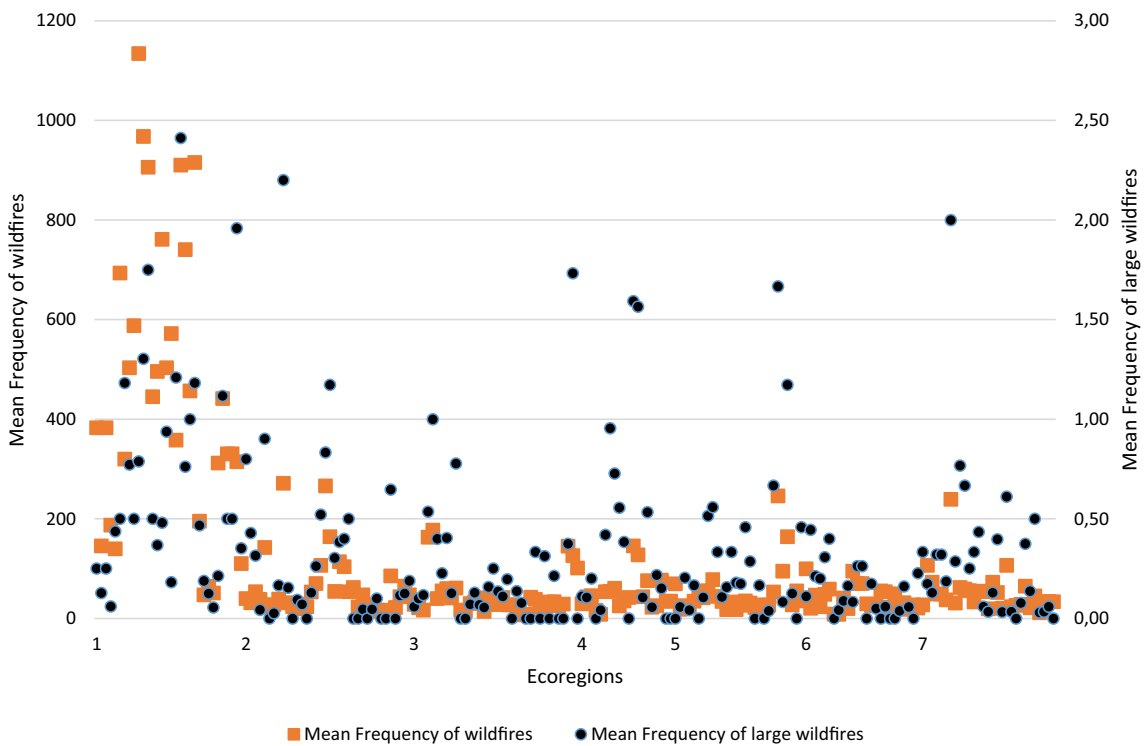
Results

Relationship between frequency of wildfires and landscape structure

The mean frequency of wildfires per UTM of the CLATERES biogeoclimatic classes in the 42 years of the study period is 114.41 with a range of variation from 1134.18 to 7.08. Of these wildfires, an average of 3% of them resulted in large wildfires. The geographical location of the wildfires indicates a high frequency in northwestern Spain. However, large fires are scattered throughout Spain (Fig. 2). The MANOVA performed using the CLATERES ecoregion classification indicates that ecoregion 1, called "Cantabrian-Galician" and which concentrates approximately the administrative delimitation of the Autonomous Communities of Galicia, Asturias, Cantabria and the Basque Country, has shown a significantly higher frequency of fires than the rest of the ecoregions. Large fires are also significantly more frequent in this ecoregion, but also in ecoregion 4, called "Mediterranean coast", which groups together approximately the Autonomous Communities of Valencia, Murcia and the Balearic Islands. Ecoregion 6, called "Manchega", which groups together approximately the Autonomous Communities of Castilla-La Mancha and Madrid, is the ecoregion with the least number of large fires during the study period. The ecoregions 2 (approximately Castilla–León Autonomous Communities), 3 (approximately Cataluña and Aragón Autonomous Communities), 5 (approximately Extremadura Autonomous Community) and 7 (approximately Andalusia Autonomous Community) showed similar number of large wildfires (Fig. 3).

The MANOVA performed with the landscape metrics indicates that the plots in ecoregion 1 are characterized by maintaining high proportions of heterogeneous agricultural areas, forest plantations, scrublands and a high diversity of land uses. Ecoregion 2 plots maintain many crops with a coarse grain of patches, little diversity of land uses and fewer roads than the other ecoregions. Ecoregion 3 is characterized by maintaining plots where forests predominate.
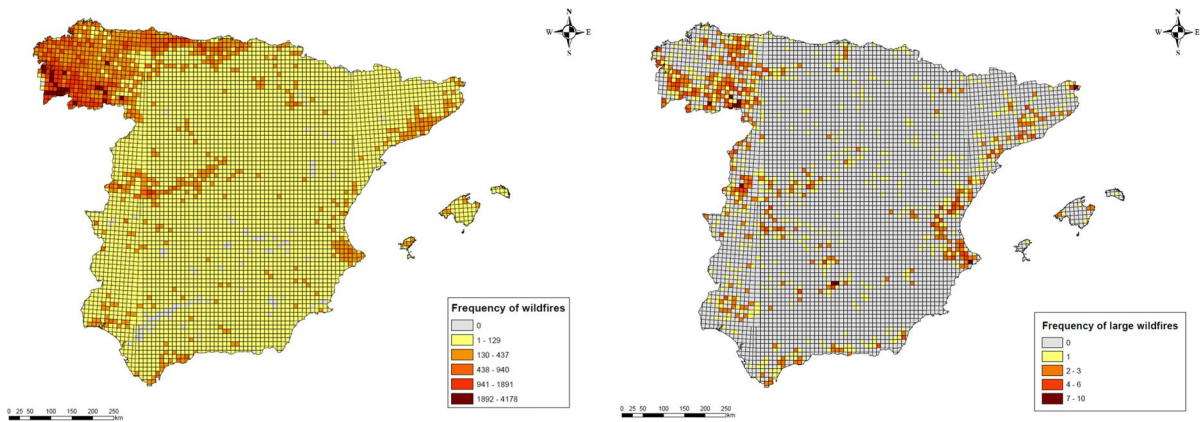
Fig. 2 Frequency of wildfires (on the left) and large wildfires (on the right) in UTM of Spanish Iberian Peninsula and Balearic Islands from 1974 to 2015. Data provided by EGIF

Parameters	1	2	3	4	5	6	7	F	Sig
Mean frequency of wildfires	459,73[a]	63,03[b]	46,36[b]	50,06[b]	50,21[b]	39,97[b]	52,19[b]	49,83	<0,001
Mean frequency of large widlfires	0,70[a]	0,31[bc]	0,23[bc]	0,39[b]	0,29[bc]	0,13[c]	0,30[bc]	5,73	<0,001

Fig. 3 Mean frequency of wildfires and mean frequency of large wildfires per biogeoclimatic classes of CLATERES classified by 7 ecoregions that are called **1** Galaico-Cantábrica, **2** Duriense, **3** Catalano—Aragonesa, **4** Litoral Mediterránea, **5** Extremadura, **6** Ibérico—Manchega and **7** Bética. The table is a MANOVA analysis of these parameters using the ecoregion type as classification factor. Duncan Post-hot test was used. Letters indicate homogeneous groups

Ecoregion 4 is characterized by its scrublands, but with a high diversity of land uses. Ecoregion 5 is dominated by "dehesas", also with a high diversity of uses and a higher density of roads. Finally, in ecoregions 6 and 7, extensive crops predominate, especially in ecoregion 7, and both have a high density of roads (Table 2). Gallery forests showed no differences between ecoregions.

Landscape metrics significantly related to wildfire frequency were heterogeneous agricultural areas and forest plantation positively and Crops area, "dehesa" area and forest area negatively. In the case of large wildfire frequency, the landscape metrics significantly related were scrublands and forest plantation positively and crops negatively (Table 3).

Quantitative evaluation of spatial resilience to wildfires

The spatial resilience to wildfire considered as the balance of landscape metrics that were significantly related to (1) all wildfires (SRI_w) in the study period and (2) only large wildfires (SRI_{lw}) was calculated using the following equations, where the metrics were weighted by the standardized coefficients of the regression models in Table 3:

Table 2 MANOVA of the landscape metrics of the 206 SISPARES plots using the ecoregion type as classification factor

Metrics	Ecoregions							F	Sig
	1	2	3	4	5	6	7		
"Dehesa" area	0.06[c]	1.21[b]	0.01[c]	0.07[c]	3.61[a]	0.15[c]	1.28[b]	14.7	<0.001
Crops area	0.53[a]	3.51[bc]	2.84[bc]	2.78[bc]	2.11[a]	4.44[c]	3.73[bc]	4.86	<0.001
Forest area	2.52[b]	3.01[b]	5.67[a]	2.54[b]	2.02[b]	2.72[b]	1.98[b]	6.99	<0.001
Heterogeneous agricultural area	2.72[a]	0.13[b]	0.30[b]	0.13[b]	0.00[b]	0.12[b]	0.26[b]	16.7	<0.001
Shrubs area	2.26[ab]	1.85[b]	1.61[b]	3.10[a]	1.51[b]	1.76[b]	1.87[b]	1.49	0.18
Riparian woodlands	0.85[a]	0.49[a]	0.26[a]	0.34[a]	0.85[a]	0.70[a]	1.00[a]	1.09	0.37
Forest plantation	3.43[a]	0.32[b]	0.35[b]	1.13[b]	0.89[b]	0.64[b]	0.70[b]	12.2	<0.001
Shannon diversity index	7.29[a]	4.65[d]	4.83[cd]	6.02[bc]	6.16[ab]	4.95[bcd]	5.31[bcd]	5.61	<0.001
Mean patch size	0.34[b]	0.73[ab]	0.51[b]	0.43[b]	0.66[b]	0.69[b]	1.16[a]	2.84	0.01
Road density	3.60[ab]	2.77[b]	3.55[ab]	3.6[ab]	4.15[a]	4.16[a]	3.92[a]	2.14	0.05

Duncan Post-hot test was used. Letters indicate homogeneous groups

Table 3 Backward linear regression models of mean wildfire frequency and mean large wildfire frequency by CLATERES biogeoclimatic class

Model	Metrics	Standardiced Beta Coefiecients	t	sig
Frequency of wildfires $R^2 = 0.44$				<0.001
	"Dehesa" area	−0.184	−2.792	0.006
	Crops area	−0.281	−3.618	<0.001
	Forest area	−0.174	−2.278	0.024
	Heterogeneous agricultural area	0.384	6.56	<0.001
	Forest plantation	0.202	3.031	0.003
Frequency of large wildfires $R^2 = 0.23$				<0.001
	Crops area	−0.197	−2.748	0.007
	Shrubs area	0.293	4.275	<0.001
	Forest plantation	0.191	2.93	0.004

The independent variables were all landscape metrics described in Table 1

$$SRI_w = 0.18 * (10 * (D/Max(D)))$$
$$+ 0.28 * (10 * (C/Max(C)))$$
$$+ 0.17 * (10 * (F/Max(F))) - 0.38 \quad (1)$$
$$* (10 * (HET/Max(HET))) - 0.20$$
$$* (10 * (FP/Max(FP)))$$

where D is "dehesa", C is crops, F is forest, HET is heterogeneous agricultural areas and FP is forest plantation; and.

$$SRI_{lw} = 0.20 * (10 * (C/Max(C))) - 0.29$$
$$* (10 * (M/Max(M))) - 0.19 * \quad (2)$$
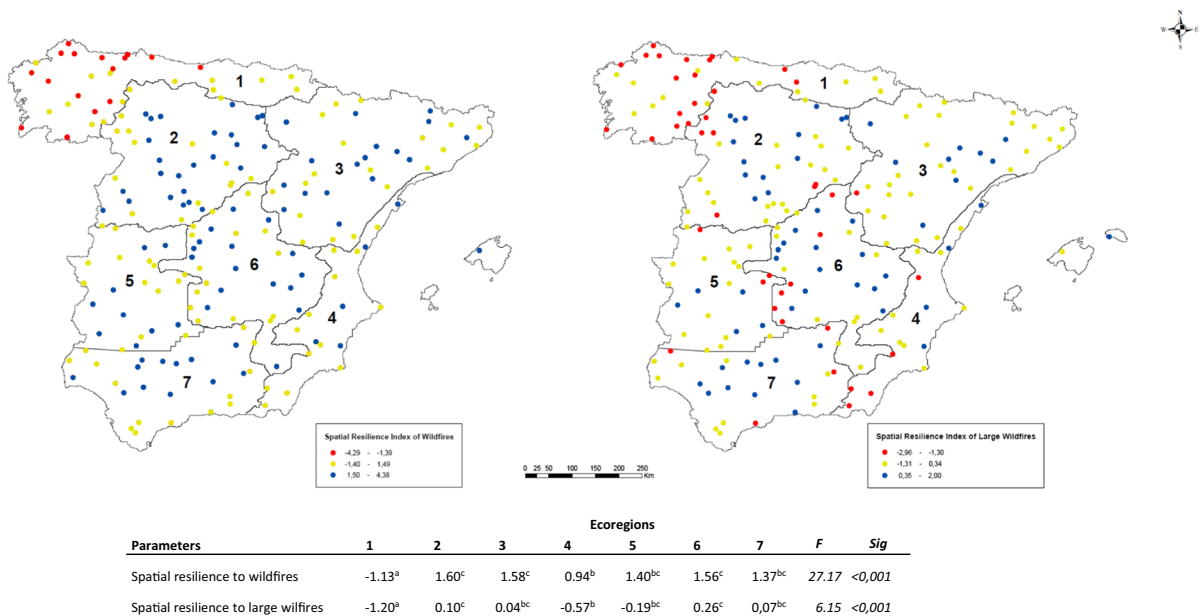$$(10 * (FP/Max(FP)))$$

where C is crops, M is scrubland, and FP is forest plantation.

Spatial resilience values to wildfire were significantly lower in ecoregion 1, while spatial resilience to large wildfires was lower in ecoregions 4 and 5, and especially in ecoregion 1 (Fig. 4).

Discussion

Relationship between rural abandonment and the historical frequency of fires in Spain

Rural abandonment (population decline and cessation of agricultural activity) was the main socio-environmental process in the EU Mediterranean countries in the last 50 years (Delgado-Artés et al. 2022). Associated with this rural abandonment, there was a process of agricultural intensification (e.g. increased irrigated land) and scrubbing and encroachment of forest areas. This expansion of forest areas was accompanied by a degradation of their ecological quality, an increase in their connectivity and a general lack of management (Martín-Martín et al. 2013; Gómez-Sanz et al. 2014; Delgado-Serrano and Hurtado-Martos 2018). The results of our study show that in all the ecoregions studied there have been wildfires and large wildfires associated with the process of shrub encroachment after the abandonment (considered as extensification process) of the maintenance of forest areas. This lack of maintenance is due to a shortage of labour,

	Ecoregions								
Parameters	1	2	3	4	5	6	7	F	Sig
Spatial resilience to wildfires	-1.13[a]	1.60[c]	1.58[c]	0.94[b]	1.40[bc]	1.56[c]	1.37[bc]	27.17	<0,001
Spatial resilience to large wilfires	-1.20[a]	0.10[c]	0.04[bc]	-0.57[b]	-0.19[bc]	0.26[c]	0,07[bc]	6.15	<0,001

Fig. 4 Spatial resilience to wildfires and spatial resilience to large wildfires in 206 plots of 4×4 km randomly located following a stratified sampling design based on the biogeoclimatic classification, CLATERES, developed by Elena-Rosselló et al. (1997). Their grouping into 7 ecoregions in Spanish Iberian Peninsula and the Balearic Islands is indicated. Ecoregions are called **1** Galaico-Cantábrica, **2** Duriense, **3** Catalano—Aragonesa, **4** Litoral Mediterránea, **5** Extremadura, **6** Ibérico—Manchega and **7** Bética. The table is an MANOVA analysis of these parameters using the ecoregion type as classification factor. Duncan Post-hot test was used. Letters indicate homogeneous groups

both for livestock grazing and for forestry tasks. Precisely these two types of land use, forest plantations and scrublands, were associated with large wildfires because of their spatial characteristics, a large area occupied with a marked homogeneity, which favours the spread of wildfires. Other types of land use, such as pastures and crops, have a low incidence of wildfires because they are continuously subject to human control, which does not allow biomass accumulation. One of the ecological effects of the process of abandoning agricultural activities is the natural recovery, determined by ecological succession, of abandoned rural areas. Beyond the renaturalisation of ecosystems and the increase of biodiversity, at least in the medium and long term (Quintas-Soriano et al. 2022), this spontaneous recovery process entails other types of consequences that can be considered socially risky and economically damaging. Specifically, the increase in plant biomass (combustible material) increases the risk of ignition of fires and, the cessation of agricultural activities causes a loss of productive options, affecting the development in rural areas (Rey-Benayas et al. 2007; Quintas-Soriano et al. 2022).

Comparatively, the different ecoregions have shown a certain regularity in relation to the frequency of large wildfires, while the total wildfire frequency has been mostly concentrated in ecoregion 1 (9 times more than in the rest of the ecoregions) and practically evenly distributed in the rest of the ecoregions (around 50 events throughout the study period). In ecoregion 1 the preponderance of large areas of scrublands and, to a lesser extent, homogeneous and unmanaged forest plantations, interspersed with heterogeneous agricultural areas, resulted in a high wildfire frequency and the highest number of large wildfires (although the average is less than 3 over the time period studied). Fire is known to spread more easily through high fuel loads and homogeneous terrain (scrublands and unmanaged forest plantations) and, sometimes, its occurrence increases spatial homogeneity generating positive feedback for wildfire spread (Loepfe et al. 2010; Marey-Pérez et al. 2021). Throughout ecoregion 1, and in Autonomous Community of Galicia in particular, decades ago forests were a complement (extraction of firewood, non-timber forest products) to agricultural and livestock activities and to obtain extra income (Chas-Amil 2007; Rodrigues et al. 2016; Díaz et al. 2018;

Urbieta et al. 2019). In this way, the daily use of the forest meant that it was accessible and fuel material was scarce (Chas-Amil 2007). However, since middle of the twentieth century, native forest stands began to be replaced by plantations with more productive species, mainly *Pinus pinaster* or *Eucalyptus* (mainly *E. globulus*) and an increase in the area of woodland (Rico and Sánchez 2018). In fact, the area occupied by *Eucalyptus* throughout ecoregion 1 has multiplied by 4.6 in the last 50 years, with Galicia and Asturias accounting for 85.67% of the total *Eucalyptus* area in these Autonomous Communities (López-Sánchez et al. 2021; Ayuga-Téllez et al. 2022). The owners of the land occupied by these plantations (98% are private) generally lacked a forestry culture and tradition and, consequently, neglected the management of their forest stands (Chas-Amil 2007). These changes in land use, from native forests to more productive artificial plantations, the lack of care of the plantations and the land restructuring derived from socioeconomic and demographic changes that promoted the presence of mosaics of land use (heterogeneous agricultural areas), increased the susceptibility of the territory to wildfires (Ortega et al. 2012a). The heterogeneous agricultural areas are fine-grained forest-agricultural mixtures were associated to ignition events much beyond what could be expectable by simply considering the total amount of these two land uses in the landscape (Ortega et al. 2012a). Fine-grained mixtures seem to enhance the competition for space and resources at the local scale in which management and traditional landowners use and perceive the landscape (Chas-Amil et al. 2010). Therefore, either intentionally or not, these heterogeneous agricultural areas, also called "mosaics" make the overall landscape more susceptible to ignition events associated to uncontrolled slash burning, woody vegetation control, etc. Conversely to our results, other authors showed evidence that some "mosaic" landscapes are more resistant to wildfire (Bertomeu et al. 2022). These differences could be due to climatic variability and the type of landscape (use and management) in which these studies are carried out. Regarding forest plantations of eucalyptus, as well as other species, a proper forest management, including measures such as removing vegetation around the base of the trees, removing all dead wood, regularly stripping bark, and maintaining cuttings at optimal rotation ages (Diaz Balteiro and Rodríguez 2006; Galizia and Rodrigues

2019), would decrease its potential susceptibility to fire. In fact, as highlighted by Fernandes et al. (2019), eucalyptus afforestation had no effect on the Portuguese fire regime although the aftermath of previous large fires increases rural abandonment in general, and of the forest as an economic resource, in particular. These consequences contribute to the homogenisation and simplification of the spatial structure of the landscape, which is the main factor in the increase of large fires, regardless of the composition of the forest.

Ecoregion 2 has retained many crops with a coarse grain of stains, little diversity of land use and less road density than the rest of the ecoregions. This ecoregion is home to the most depopulated and ageing municipalities, mainly due to the lack of transport infrastructure (it has the lowest road density of the ecoregions studied) and services in comparison with other Spanish mountain areas. The population has been concentrating in industrial cities and rural areas have been reducing their population, reaching a complete demographic stagnation (Martínez and Delgado 2013). The extensive cereal-steppe rainfed farming system characteristic of this ecoregion and also ecoregion 6, combining cereal crops, fallow land, leguminous plants, and sheep, maintains a spatial pattern of coarse grains and low accumulation of biomass fueled by grazing. Despite some intensification of arable crops (Serra et al. 2014), the spatial pattern of large crop plots and their extensive management are key to avoid a high frequency of fires (Costafreda-Aumedes et al. 2013; Salis et al. 2022). So, it is consistent to think that if there is little fuel to burn in extensive cultivation, the chances of large wildfires will also be low and in the sense that we have given to spatial resilience in this article, this parameter will be high.

The most outstanding feature of ecoregion 3 is the high proportion of forests or woodlands. At the regional scale, fires are closely related to vegetation type. Scrublands and pine forests are more prone to fire than broadleaved evergreen forests and especially deciduous forests. This pattern is related to the Mediterranean-type climate (Díaz Delgado et al. 2004). In this ecoregion, the relatively high presence of native forests and a diversity of land uses resulted in a low fire frequency. Especially in Catalonia, there has been an expansion of woodland due to the abandonment of pastures and crops and forests occupy 65% of the territory with a higher proportion of Mediterranean

forest (holm oak, Aleppo pine, Scots pine, cork oak, gall oak) but also with forests characteristic of the Central European and subalpine biome (beech, oak, chestnut, black pine) (Díaz-Delgado et al. 2004; Badia et al. 2019). In ecoregion 4, large wildfires are also associated with changes in land use, especially linked to agricultural concentration and intensification, leaving areas of abandonment and increasing the area of woodland and scrubland in a similar way to ecoregion 1. This process of abandonment and scrubland in inland areas of the ecoregion has probably combined with the increase in tourism and second homes due to a process of coastal urbanisation (i.e., a concentration of population and economic activities along the coastal zone and in its immediate vicinity) that has occurred throughout the Spanish Mediterranean coast, aggravating the likelihood of wildfires (Serra et al. 2014). This process led to the so-called empty urbanism that generated urbanised deserts with the abandonment of many agricultural plots due to the expectations of enormous capital gains derived from the approval, or even the mere processing of land-use plans that classified them as "land for development" and, simultaneously, biomass accumulation (Burriel 2015). Moreover, this land use evolution combined with a period of severe droughts produced a favourable environment for large wildfires throughout the 1980s (Moreno et al. 2014).

In ecoregion 5, the results show that extensive agro-silvo-pastoral systems of "dehesas" dominate but accompanied by a high diversity of uses and a high density of roads. The "dehesas" have an open tree layer, dominated mainly by evergreen Mediterranean holm oaks and to a lesser extent by deciduous oaks, ash and wild olive trees with extensive livestock farms (sheep, cattle and pigs) and cereal crops in long rotations (Cañellas et al. 2007). The spatial pattern of this traditional use seems resistant to the incidence of fire (Ortega et al. 2012a). Finally, in ecoregions 6 and 7, extensive cultivation predominates, especially in the latter, and a high density of roads was found in both ecoregions. In ecoregion 6, the results show the preponderance of extensive cultivation with low accumulation of combustible biomass that hinders the spread of wildfires, turning them into large fires. In fact, it is the ecoregion with more crops, of considerable size plots and with a high road density and, at the same time, it does not present a remarkable intensification and urban sprawl (Serra et al. 2014). A spatial

characteristic of the landscape of ecoregion 7 is the massive presence of woody crops (i.e. olive groves), largely in monoculture format (Rescia et al. 2017). At the same time, Andalusia, which forms part of this ecoregion, is the Autonomous Community with the largest number of large estates (see Table 2) and a high proportion of private farmland.

In general terms, from our results, it can be inferred that the complex socio-ecological context of Spain's rural landscapes (an ageing, small and declining rural population, strong predominance of private land ownership, high fire risk that prevents investment in options other than short rotation forestry) suggests that more sustainable and resilient landscapes can only be achieved through institutional regulations and subsidy policies that ensure the maintenance of key ecosystem services for the well-being of their people (Gómez-González et al. 2018).

Usefulness of resilience indices

Indicators are tools that concentrate (simplify) information and are used to measure objectively and make their interpretation simple and easy to communicate. The spatial resilience index developed by Rescia and Ortega (2018) and modified by Ortega et al. (2020), is composed of different indicators (metrics) of the spatial structure of the landscape. In our study, two spatial resilience indices have been measured, one against fire and the other against large wildfires for the ecoregions considered. According to the SRI referring to total wildfires, ecoregion 1 presented the lowest resilience values. This means that the spatial structure of the dominant landscape in this ecoregion is more susceptible to wildfire than the rest of the ecoregions. According to Marey-Pérez et al. (2021), in this ecoregion, with one of the most severe wildfire records in Western Europe, resilience indicators should be related to changes in land-use planning and management aimed at minimising the effects of wildfires. Such management should not be focused exclusively on timber production at the producer scale (in Autonomous Community of Galicia, properties are on average 0.3 ha, Chas-Amil 2007) but on a broader spatial strategy by organising management activities at the landscape scale, during and after forest fires to reduce wildfire risk and adverse effects (Wollstein et al. 2022). In management, the

incorporation of analytical and visualisation techniques to understand and exploit the use of Deep Learning in the context of wildfire ignition risk prediction is of interest (Pais et al. 2021). The rest of the ecoregions present relatively low values of spatial resilience, although higher than ecoregion 1. Ecoregion 4 presents a spatial structure with lower spatial resilience due to its abundance of shrublands.

In terms of resilience to large wildfires, the SRI values have been lower than the SRI for wildfires. Ecoregion 1 maintains very low resilience values and ecoregions 4 and 5 have a much lower resilience to large fires, especially ecoregion 4, than to wildfires. Autonomous Community of Galicia, located in the northwest of the country within ecoregion 1, has focused its productive system on the forestry sector (50% of national timber production) and on the dairy livestock sector (40% of national dairy production). During this process, which spanned the last 50 years, the areas covered by woody vegetation (trees and scrub) increased very significantly, both due to the expansion of forest plantations and the ecological succession, leading to a considerable increase in the amount and continuity of biomass present on the land (Marey-Pérez et al. 2021). Thus, this Autonomous Community is characterised by a high percentage of forest area, representing more than 60% of the region's surface and accounting for 11% of the total forest area in Spain (Marey-Pérez et al. 2014; Chas-Amil et al. 2015; Rico and Sánchez 2018). As for ecoregion 4, although crops favour resilience against large wildfires, the presence of a high diversity of uses and a relatively high density of roads could act as promoters of wildfire spread. In this regard, Ortega et al. (2012a) found that high road density contributes to fire occurrence. In the rest of the ecoregions, the spatial resilience index to large fires has also decreased compared to that of wildfires because, due to the spatial structure of their rural landscapes, in many cases scrubby, the spread of wildfires would be favoured.

Ultimately, the application of the concept of spatial resilience provides the ability to address the effects of anthropogenic and ecosystem disturbances at scales relevant to managers. Assessing and interpreting the spatial resilience of a landscape through an indicator requires understanding the effects of changes in landscape composition and configuration

due to anthropogenic and natural disturbances (Chambers et al. 2019). Recent fire management (suppression policy) in Spain aims to reduce wildfire frequency, but as our results suggest, coinciding with those of Moreno et al. (2014), fire suppression (that includes all the firefighting activities in the "response" phase of the fire management cycle) can be effective in controlling small wildfires. However, this policy, which causes a build-up of fuel, seems to be ineffective in preventing or controlling large wildfires under extreme weather conditions, especially in recent years in a context of climate change. Different studies show contradictory results, some of them recommending that fire management should focus more on the conservation of the traditional rural mosaic to avoid further increasing fuel continuity and wildfire risk (Loepfe et al. 2010; Ortega et al. 2012a) and, according to our results, some traditional uses with large and relatively homogeneous patches ("dehesas") may be less prone to wildfire. Ultimately, more attention should be paid to the emergence of new wildfire environments in previously fire-free environments and management actions need to be adjusted to these new conditions to maintain Mediterranean forests under a changing climate (Karavani 2018).

Limitations and future directions

This study has several limitations, and future studies should be completed. The most relevant of them is that the spatial resilience of the landscape, dependent on its spatial structure, is a capacity of the landscape that varies over time, i.e. with the dynamics of the territory itself (changes in land use and land cover, disturbances regime). However, in this study we have only considered the current spatial structure of the territory, beyond its history over time, to use the spatial resilience index of the current landscape as a tool for future territorial management. From the calculated index, using indicators of the current spatial structure, a desired structure focused on resilience to wildfires and large wildfires can be planned. For future studies, the incorporation of the temporal component in the spatial variation of the territory (essentially changes in land use and land cover) should be considered to relate this spatial variation over time to the evolution

of the spatial resilience of the landscape to the temporal frequency of fires.

From a temporal point of view, landscape modelling can use either static or dynamic approaches. Static approaches assume that the landscape is in equilibrium with its environment and do not take into account transient phases. Landscape heterogeneity is, therefore, a simple mapping based on the heterogeneity of the exogenous factors considered. The main advantage of a static approach is that it can be a good starting point for other modelling approaches. The main drawback is that the mechanisms determining spatio-temporal patterns are not explicitly included in the models, suggesting that landscapes are considered in equilibrium and that the models therefore ignore transient behaviour and temporal factors. This limits cause and effect analyses and restricts extrapolations to the range of factors used to calibrate the model (Gómez-Sanz et al. 2014).

Conclusions

In the last decades, the land abandonment and agricultural intensification of the rural landscapes, led to changes in the land management and the composition and spatial configuration of land uses. These changes resulting in a different response capacity of the rural landscape to wildfire, being more resilient or vulnerable depending on the spatial structure resulting from the changes. Many traditional rural cultural landscapes in the Mediterranean Region are linked with wildfire as a tool to manage it, together with grazing and firewood extraction. In Spain, most wildfires are still linked to agricultural activities and, therefore, from the knowledge of its history of wildfires and their evolution with the rural landscape we can learn about how to manage and invest in the sustainability of rural landscapes.

Our findings on the analysis of the spatial structure of Spanish rural landscapes at the ecoregion scale showed significant differences in the total frequency of fires, with ecoregion 1 (Galicia, Asturias, Santander, Basque Country) suffering 9 times more fires than the rest of the ecoregions studied in the last 42 years. In the rest of the ecoregions, the total wildfire frequency was similar. The pattern of large

wildfires is different, although it occurs more in Norwest, other ecoregions also show incidence of large wildfires. Among the landscape characteristics (of the metrics used) that were significantly related to fire frequency, heterogeneous agricultural areas and forest plantation were found to be positively related to fire frequency while crops, "dehesas" and forests were found to be negatively related to fire frequency. In the case of large fire frequency, the landscape metrics significantly related were scrublands and forest plantation positively and crops negatively. Based on these objectively detected descriptor metrics as indicators, a composite resilience index was developed for wildfires and another for large fires. Values obtained for spatial resilience index to fire were significantly lower in ecoregion 1, while spatial resilience to large fires was lower in ecoregions 1, 4 and 5. The analysis has been carried out by ecoregions because of their approximation to the Autonomous Communities as management units and, in this way, the resilience indicators could be used as early warning tools for fires and would allow the design of management and prevention policies (forestry, essentially) for Spanish rural landscapes.

Declarations

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