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Research article

# Regional fire scenarios in Spain: Linking landscape dynamics and fire regime for wildfire risk management

Cristina Montiel Molina[a,*], Oskar Karlsson Martín[a], Luis Galiana Martín[b]

[a] Department of Geography, Complutense University of Madrid, Spain
[b] Department of Geography, Autonomous University of Madrid, Spain

A R T I C L E I N F O

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A B S T R A C T

Fire scenarios are multiscale land-type planning units for a fire regime with different applications at national, regional, and local scales. The main aim of this research is to implement a methodology integrating landscape dynamics and wildfire risk from a context-specific approach, to identify current fire scenarios at a regional scale in the Spanish Central Mountain Range. These homogeneous areas are linked to different stages of a territorial dynamics model called wildfire generations and related to land use diversity and land management trends. A place-based methodology has been developed to characterize fire scenarios using Geographic Information Systems and statistical analysis, resulting in analytical and diagnostic mapping that can be used as a decision support tool for spatial planning and wildfire risk management. Its implementation has led to the delimitation of 91 discrete geographic units in the Central Mountain Range, classified according to wildfire generations and land use-land cover criteria. In conclusion, the fire scenarios concept is a potential approach to manage uncertainty by moving from the operational level of fire suppression to the strategic level of integrated fire management.

## 1. Introduction

Wildfires are one of the most important causes of forest ecosystems disturbance. However, they are not only a threat to the ecosystems themselves but to the local population and their assets, due to the expansion of scattered urbanization in forest areas. Over the past decade, as wildfires have had major impacts on society, there has been a growing interest in understanding the anthropic factors explaining fire activity with significant research into the social aspects of fire (Czaja and Cottrell, 2014; McCaffrey, 2015). Humans affect the fire regime directly by initiating and suppressing fire, and indirectly through fuel management and fire policies, the type and intensity of land use, and changes in population and lifestyle (Montiel and San-Miguel, 2009; Moreira et al., 2011; Turco et al., 2016). The collapse of traditional rural socioeconomic systems in Mediterranean countries since the second half of the 20th century has resulted in depopulation and abandonment of land management in rural areas, with a dramatic expansion of the wildland-urban interface (Galiana, 2017; Moreno et al., 2014; Viedma et al., 2015) Nevertheless, the socioeconomic drivers of fire are not as well-known as the biophysical ones (Fernandes, 2016; Vilar et al., 2016).

Recent land use and land management trends have destabilized forest ecosystems and rural areas, leading to new fire regimes characterized by large wildfires and increasing uncertainty. It is essential to understand this global land system change in local and regional environments (Keeeley et al., 2012; Mazzoleni et al., 2004). A change of attitude is also needed to adapt to this new reality. To inform the management of socioecological systems and optimize the effectiveness of prevention, vigilance and suppression measures means defining the specific factors pertaining in each of the possible fire scenarios, as each one requires a different strategy to fight wildfires (Costa et al., 2011).

Thus, the concept of fire scenarios refers to the contextual factors of a fire regime, i.e. the environmental, socioeconomic and policy drivers of wildfire ignition and propagation on different spatial and temporal scales. This is a land-type planning unit schema, conceived as a set of homogenous spatial areas in terms of ignition conditions and fire spread patterns. It is therefore a landscape-based concept related to dynamic human/environmental interactions with a fire regime (Montiel and Galiana, 2016). Fire scenarios can be applied to understand the structural causes of the current wildfire problem linked to the socio-ecological system processes of stability, resilience or destabilization (Bastrup-Birk, 2016; Mazzoleni et al., 2004; Viedma et al., 2015).

Within this conceptual framework, the two basic assumptions underlying this research are the following:

* Corresponding author. Department of Geography, Faculty of Geography and History, Complutense University of Madrid, c/ Profesor Aranguren, s/n. 28040, Madrid, Spain.

*E-mail addresses:* crismont@ucm.es (C. Montiel Molina), oskar.karlsson@ghis.ucm.es (O. Karlsson Martín), luis.galiana@uam.es (L. Galiana Martín).

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(1) Fire behavior is largely dependent on landscape patterns, and both landscape and fire have historically evolved together (PCF, 2013; Fernandes et al., 2014).
(2) The spatial variability of wildfire risk depends on the stage of human ecodynamics, i.e. the processes of stability, resilience and change in socioecological relationships or systems (Fitzhugh et al., 2018).

The aim of this paper is to implement the method defined for characterizing fire scenarios at an intermediate operational spatial scale (Montiel and Galiana, 2016), to identify the existing planning units for a fire regime in the Central Mountain Range, and to demonstrate the value of this powerful decision support tool for preparedness and wildfire risk mitigation.

## 2. Theoretical basis

The theoretical basis of this research is socioecological systems theory, which can be used to understand the complexity of socio-spatial structures and how they function from a dynamic approach, and the wildfire generations model (Rifà and Castellnou, 2007; Castellnou et al., 2009; Montiel and Galiana, 2016). In fact, the most common social sciences approach to wildfire risk in Mediterranean climate ecosystems has been to apply socioecological systems theory. This is the basis of the natural hazard paradigm in Geography, which considers that “the source of disaster is rooted in the relationship between people and their environments” (O'Brien et al., 2010). Likewise, socio-ecological systems theory considers territory as a humanized space, constructed over time through an ongoing dialectic between its two principal components: ecosystems and people. Historically, fire has been present as a land management tool and as a disturbance in the landscape (Turner, 2010; Smith et al., 2016; Scott, 2018). Socio-ecological systems theory can deal with the complexity of socio-spatial structures and dynamics, which define ignition and fire propagation factors as the key issues of wildfire risk (Martínez et al., 2009; Montiel and Herrero, 2010; Moritz et al., 2014; O'Connor et al., 2011; Coughan and Petty, 2012).

On the other hand, the wildfire generations model, developed within the framework of fire management in Mediterranean climatic regions, describes and explains the appearance and transformation of large wildfires in relation to landscape dynamics. This is an integrative conceptual approach which relates fire types (classified according to their characteristics including spread rate and intensity) to a specific level of landscape progression within the framework of forest transition theory (Perz, 2007; Costa et al., 2011). The aim of the wildfire generations model is to analyze and interpret the dynamic interaction between land use, land management systems and fire behavior, to understand the tipping points and non-linear evolution of the fire regime (Castellnou et al., 2010; Costa et al., 2011; Montiel and Galiana, 2016).

This systemic and integrative theoretical approach enables a link between Pyrogeography, which provides an understanding of the fire footprint on the landscape at different spatial and temporal scales (Bowman, 2015; Keeeley et al., 2012), and the landscape character assessment methodology, which uses multiscale spatial differentiation as a result of the unique combination of natural and human elements and features that make landscapes distinctive (Swanwick, 2002). Finally, the fire scenario concept, which refers to the permanent interaction between fire and landscape and its influence on the character of the fire regime (Loepfe et al., 2010; Fernandes et al., 2014), is very close to the concept of firescape, devised to understand human-fire interactions and the role of fire in the landscape as a degradation or regeneration factor (Smith et al., 2016).

## 3. Material and methods

### 3.1. Study area

The Central Mountain Range natural region covers a surface area of over two million hectares, with around 85% forest. It includes 672 municipal areas in 7 provinces (Cáceres, Salamanca, Ávila, Toledo, Segovia, Madrid, and Guadalajara), and 4 political regions (Extremadura, Castilla y León, Madrid, and Castilla-La Mancha). This is an elongated mountain range, running west-east in the central Iberian Peninsula, composed of clearly differentiated massifs including the Massifs of Gata, Gredos, Guadarrama and Ayllón. It is predominantly rural in character, although the Guadarrama Massif in the vicinity of Madrid and some areas near the provincial capitals present intensive housing developments related with metropolitan dynamics and urban sprawl processes.

The Central Mountain Range is one of the areas in the Iberian Peninsula most affected historically by forest fires, particularly in the province of Cáceres (Araque, 1999; Montiel, 2013). At a national scale, four fire scenarios have been identified in the study area, according to the effects of major land-use changes and based on the most relevant structural characteristics of fire behavior (Montiel and Galiana, 2016):

1. *Croplands and grasslands of the Central Mountain Range valleys and foothills*: This national fire scenario is found in specific sectors of the graben between mountain ranges which configure the massifs and sierras of the north face of this natural region. The vegetation cover has been intensely transformed by agricultural activity. Non-irrigated cereal crops predominate, with pastures on the valley floors, and forested areas are reduced to the stony piedmont sectors. Settlements are found near the rivers and, except for the city of Segovia, are generally small rural nuclei with low density, rapidly aging population.
2. *Dehesas and pasture lands in te Central Mountain Range foothills*: This national fire scenario is found in the foothills surrounding the mountain massifs to north and south, forming the transition area between the mountain ranges and the Duero and Tajo river basins. The main land cover here is *dehesa* pastureland. The characteristics of the settlement system are different in the Guadarrama Massif near Madrid, where urban sprawl has led to the expansion of wildland-urban interface areas, from the rest of the region, where small, concentrated rural settlements with low population persist.
3. *Massifs and forested ranges of the Central Mountain Range*: This national fire scenarios consists in an extensive mountainous alignment, arranged in successive elevated ranges rising to altitudes over 2000 m presenting marked climatic contrasts between the north and south facing slopes. This scenario is forested and ecologically very diverse. The small rural settlements on the valley bottoms present concentrated building patterns. In the areas surrounding the cities of Madrid, Segovia and Ávila developments of second homes are found around the traditional nuclei, forming urban-forest interface areas.
4. *Agro-forestry mosaic of the Central Mountain Range foothills*: This fragmented national fire scenario corresponds to the transition zones between the mountain environments and the agricultural plains of the Duero and Ebro river basins. The predominantly flat topography has facilitated land use for agricultural and livestock farming. The forest formations cover the sectors with the most irregular relief, particularly the *dehesas* and shrublands. The settlements here are small rural nuclei, except in the hinterland of the Madrid metropolitan region and in the province of Avila, where potentially highly dangerous urban-forest interface zones have developed.

The study area was divided into a total of 1969 watersheds, with an average area of 1057 ha to apply the methodology defined below and obtain the regional fire scenarios (Fig. 1).

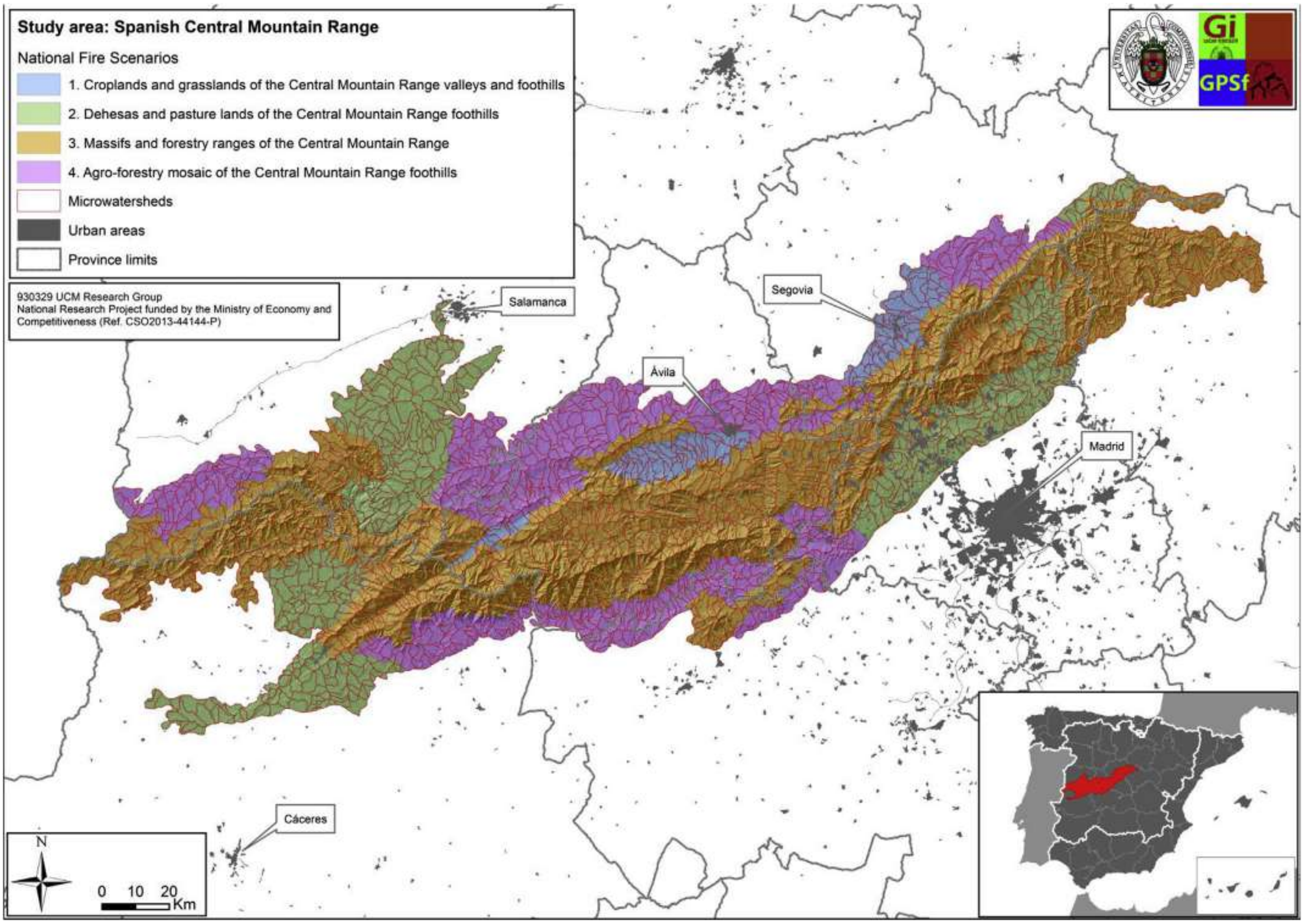


**Fig. 1.** Study area: Spanish Central Mountain Range.

**Table 1**
Wildfire generation stages.

| Wildfire Generations | Landscape structure and dynamics | Fire behavior |
|---|---|---|
| 0. Pre-first generation | Landscape mosaic corresponding to maintenance of farmland management and fire culture | Small and medium size wildfires of low intensity and propagation speed |
| 1. First generation | Continuity of forest mass as a result of agricultural abandonment | Long perimeters and high propagation speed |
| 2. Second generation | Increased fuel load due to abandoning of farmland and traditional forest management | Complex wildfires of high intensity and high propagation speed; start of secondary ignition sites |
| 3. Third generation | Homogeneous forest with high densities and vertical continuity due to prolonged lack of forest management (30–50 years) | Crown fires that overwhelm tactical intervention capacity; multiple secondary ignition sites. Large wildfires, more than 20,000 to 30,000 ha. |
| 2. Fourth generation | Increase of scattered housing developments in forest land with third generation characteristics | Very complex wildfires, with multiple emergencies in wildland-urban interfaces. |

**Table 2**
Threshold values of the cluster analysis.

| | Cluster | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| Forest land (with vegetation cover fraction > 70%) | 75% | 0% | 0% | 0% | 0% | 95% |
| Agricultural land | 0% | 20% | 0% | 5% | 100% | 0% |
| Forest progression | 0% | 15% | 90% | 0% | 0% | 70% |
| Agricultural abandonment | 20% | 5% | 0% | 95% | 0% | 0% |

### *3.2. Spatial analysis and territorial dynamics*

Considering fire scenarios as land-type units which are defined through the analysis and interpretation of various spatial factors, Geographic Information Systems (GIS) and statistical analysis were the main techniques applied to process and obtain the information needed to identify areas of homogeneous fire spread patterns. ArcGIS for Desktop 10.3 was used for mapping and spatial analysis and SPSS 23 for statistical analysis.

The first stage of this methodology focuses on land use/land cover (LULC) changes to describe the fuel structure related to the different wildfire generations (Montiel and Galiana, 2016; Rifà and Castellnou, 2007). The concept of wildfire generation stems from a model of fire behavior that shows the progression towards the predominance of large wildland fires according to the variations in fuel build-up and spatial

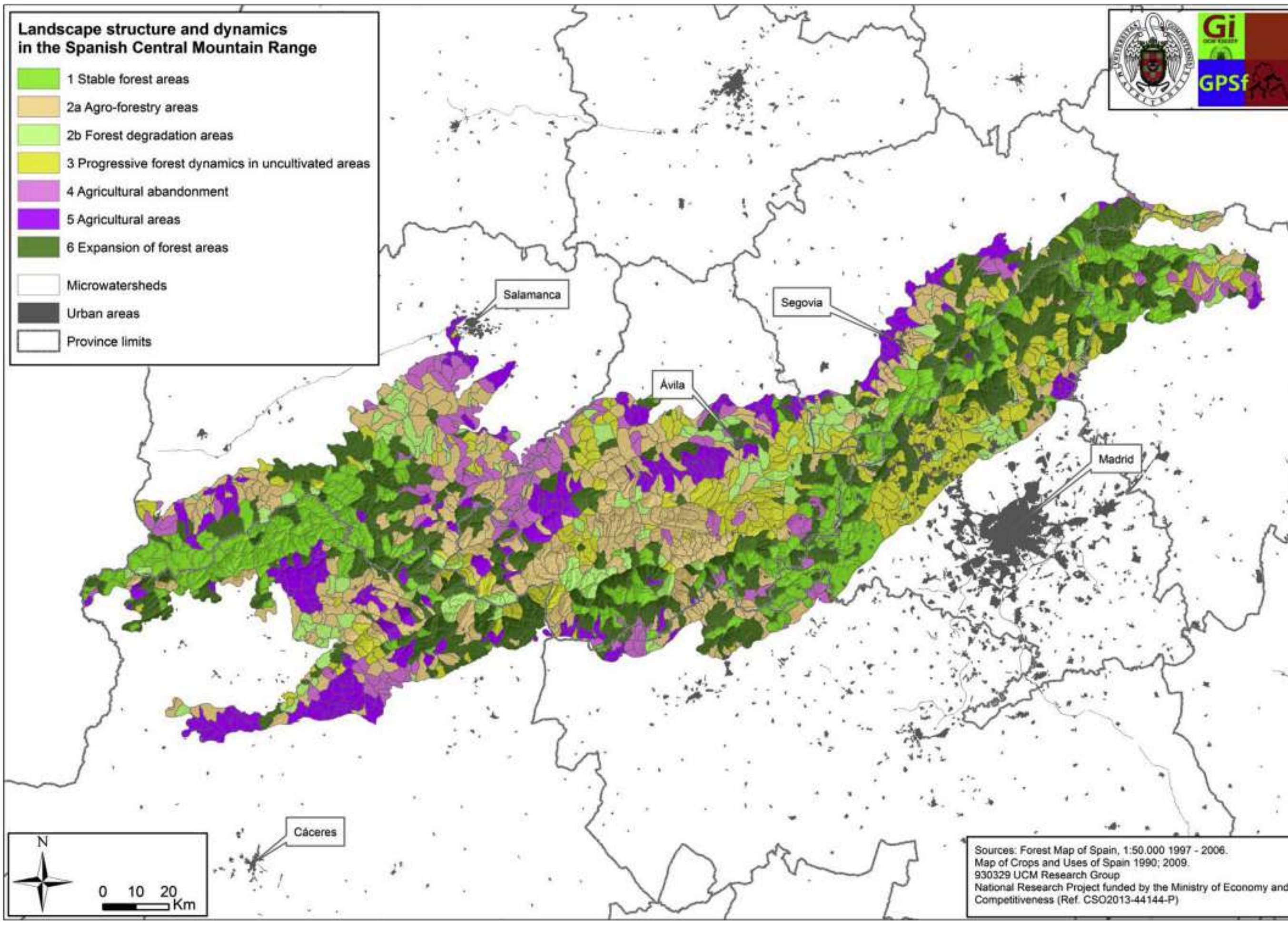


**Fig. 2.** Landscape structure and dynamics in the Spanish Central Mountain Range.

arrangement of housing within a territorial and temporal context (Table 1).

Four variables were selected to classify the fuel structure according to the wildfire generations model: 1. Forest land cover; 2. Agricultural land cover; 3. Agricultural abandonment 1990–2009; 4. Progressive forest dynamics, i.e. the progress towards higher density vegetation 1990–2009. The main data sources used to assess these spatial variables are the following:

- Forest Map of Spain 1:50.000 (MFE50, 2007)
- Crops and Uses Map of Spain 1:50.000 (MAPA, 1990; MAPA, 2009)
- Third National Forest Inventory 1997–2007 (IFN3, 2007)
- Settlements map of Spain 1:50.000 (TRAGSATEC, 2005)

The spatial analysis unit applied for its multiscale aggregation potential is the watershed derived from a digital elevation model. In this case, the digital elevation model was processed to obtain 1969 micro-watersheds with an average area of 1057 ha. The percentage coverage for each variable considered was calculated for each basic spatial unit, obtaining detailed graphic information on LULC structure and trends at watershed level. Next, using K-means cluster analysis, the micro-watersheds were grouped in six clusters:

- Cluster 1: Stable managed forest
- Cluster 2: Agro-forestry mosaic and forest degradation areas
- Cluster 3: Progressive forest dynamics in non-cultivated areas
- Cluster 4: Agricultural abandonment and natural regeneration processes
- Cluster 5: Stable productive agricultural areas
- Cluster 6: Expansion of forest areas

These clusters emerge from all the case units (watersheds), and are representative of the territorial dynamics, i.e. the different LULC stability or change processes within the regional context. This context must be taken into account to weight the influence of socioecological variables and their interactions in determining changes leading to shifts in fire behavior (Beilin and Reid, 2015; Turco et al., 2016; Viedma et al., 2015).

The threshold values represent the centers of the classes resulting from the K-means cluster analysis, and therefore represent the mean values for the definitory variables for each cluster or aggregation (Table 2). The variables are independent from each other and do not represent the total coverage for a specific moment, as two of them – agricultural abandonment and progressive forest dynamics - represent change between 1990 and 2009. Therefore, the sum of the four variables is not necessarily 100%.

Next, the forest ecosystems (clusters 1, 2, 3 & 6) were analyzed in depth using ecological and management criteria, considering (a) the main forest tree species and (b) the type and level of forest management. This is critical information to assess fuel availability and fire spread patterns for the spatial characterization of wildfire generations.

Finally, assessment of the settlement model is a key factor to analyze human presence in the area, the urban sprawl process and the expansion of the wildland-urban interface (WUI) (Galiana, 2017). With this aim, spatial analysis units with housing developments were classified in five groups according to existing urban areas and the area percentage

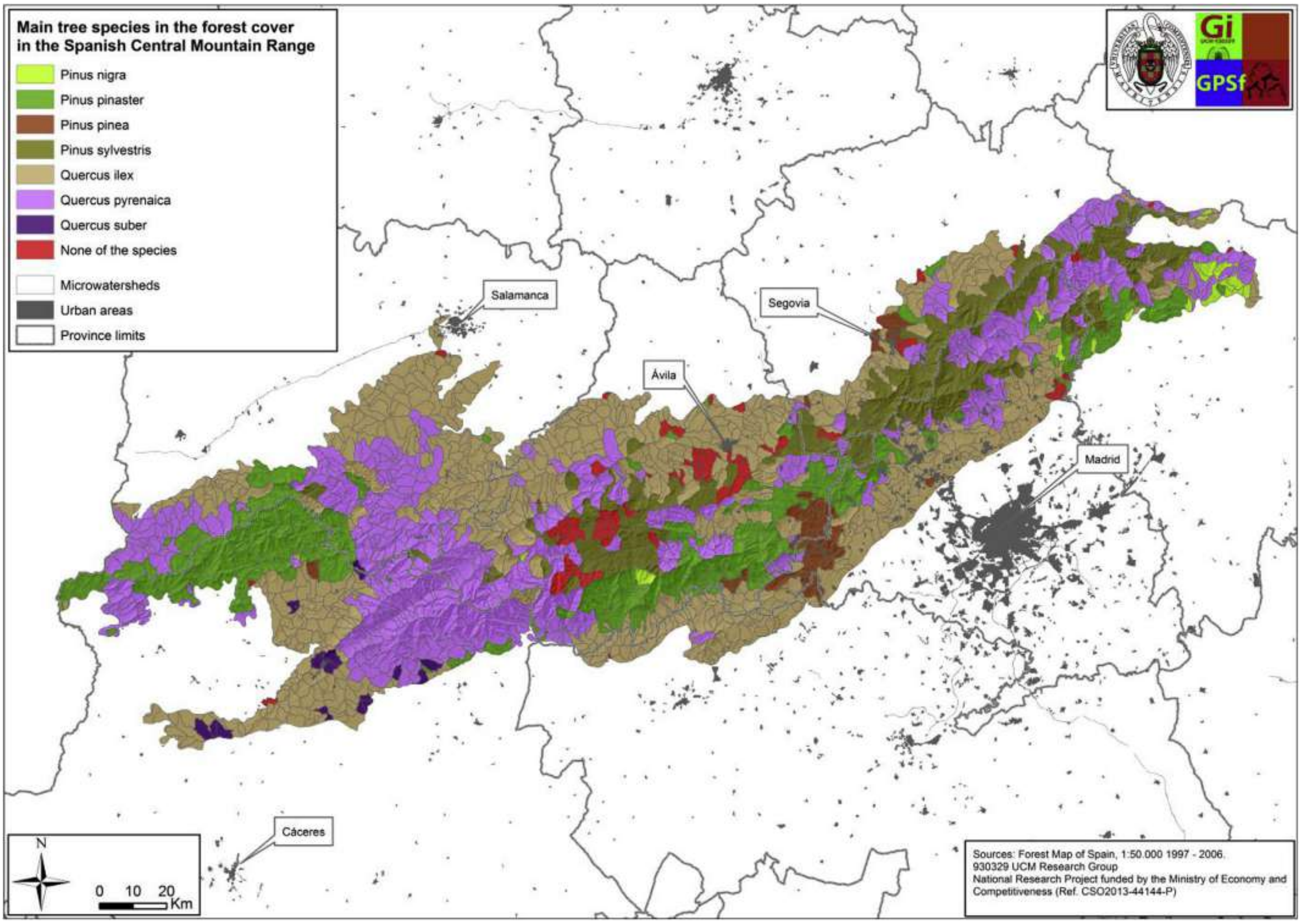


**Fig. 3.** Main tree species in the forest cover in the Spanish Central Mountain Range.

covered by urban settlements or scattered buildings in dense forest stands:

1. Watersheds with at least 50% urban area.
2. Watersheds with at least 20% urban area and 30% forest land cover, with vegetation cover fraction higher than 70%.
3. Watersheds with at least 5% urban area and 30% forest land cover, with vegetation cover fraction higher than 70%.
4. Watersheds with 30% forest land cover, with vegetation fraction higher than 70%, contiguous with class 2 watersheds.
5. Watersheds with at least 5% scattered buildings and 30% forest land cover, with vegetation cover fraction higher than 70%.

The end aim at this stage of the method is to assess the spatial patterns of the territorial dynamics, i.e. the effects on the landscape of land management abandonment and housing development.

### 3.3. Integration of the spatial analysis variables

The analytic and diagnostic mapping produced was used to identify and characterize the land-type scenarios at an intermediate planning and management scale (1: 25.000, 1: 50.000), corresponding to the landscape configuration scale defined by the European Landscape Convention: "an area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors" (Déjeant-Pons, 2006).

The delimitation of the regional fire scenarios was based on the limits of the micro-watersheds but is coherent with the landscape character assessment units and nested in the national fire scenarios (Montiel and Galiana, 2016). Photo-interpretation of aerial images, geovisual analytical methods and fieldwork techniques were used to integrate the human ecodynamics data produced into discrete geographic units corresponding to a homogeneous spatial area of a specific wildfire generation stage. The outcome is the cartographic representation of the wildfire generation stages, differentiating the LULC categories which impact on the fire/landscape interaction.

## 4. Results and discussion

### 4.1. Spatial analysis and diagnosis of human-environment dynamics and wildfire risk at the regional scale

The Central Mountain Range forms part of a series of mountainous regions in the central Iberian Peninsula which are characteristically disadvantaged rural areas with a declining, aging population, and low economic activity (Montiel and Herrero, 2010). This continuing rural character contrasts with the general socioeconomic trends of urban development and industrialization and has led to a time lag and slower rhythm of the dynamics of land management abandonment and housing developments, which affects the fire-landscape interaction.

The spatial variables explaining these territorial dynamics are (i) forest land cover, (ii) agricultural land cover, (iii) agricultural abandonment, (iv) progressive forest dynamics, (v) forest tree species, (vi) forest management, and (vii) settlement model. These spatial variables have been mapped in order to identify the land-type fire scenarios at the regional scale.

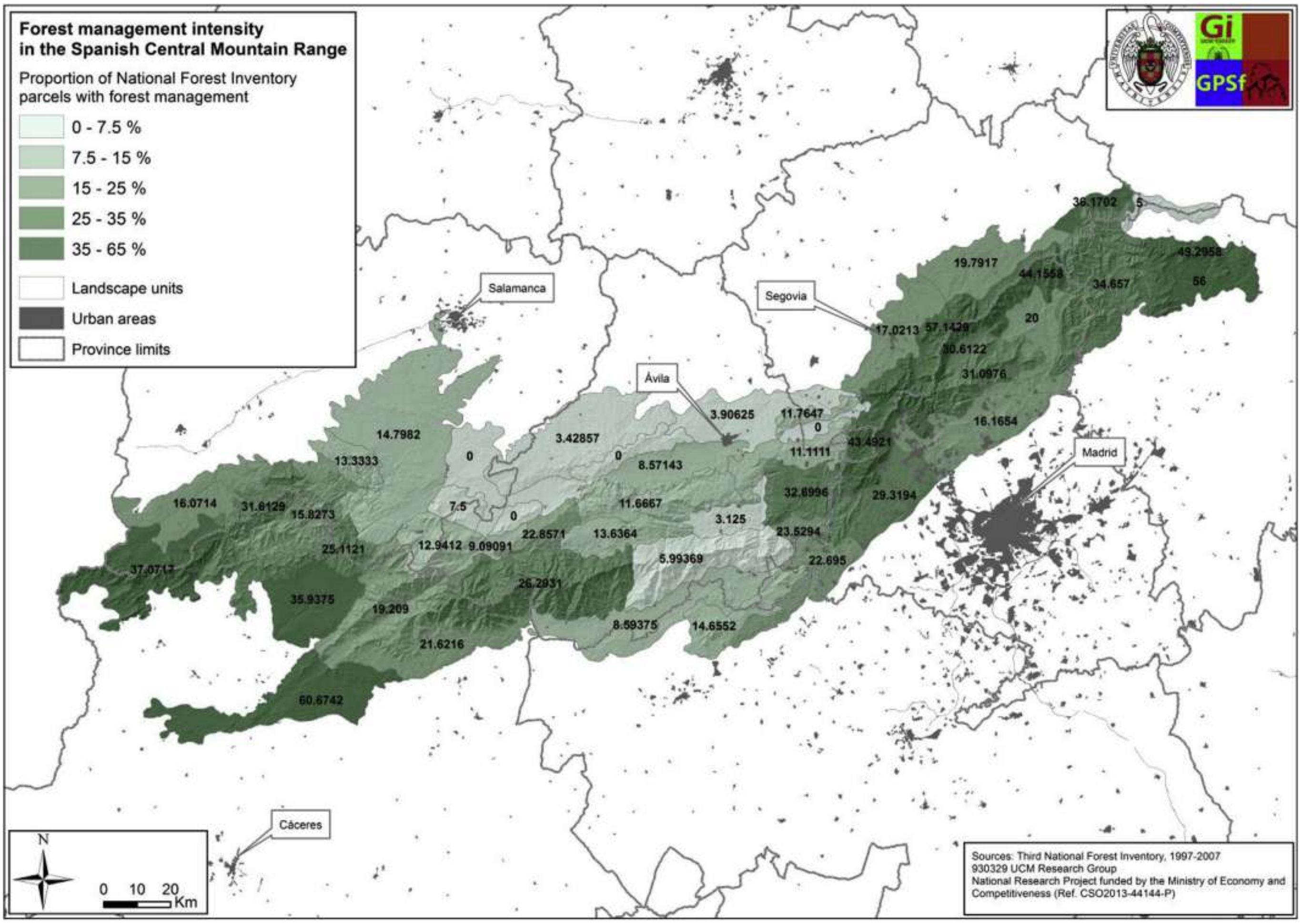


**Fig. 4.** Forest management intensity in the Spanish Central Mountain Range.

From a structural point of view, the cluster analysis of the LULC variables highlights the surface area and contiguity of stable forest areas (class 1: 343,560 ha) and agricultural areas (class 5: 213,929 ha) in this natural region. A dynamic approach highlights forest progression processes, consisting of a gradual progression of forested areas from shrubland to full tree cover, following various steps in their ecological succession (classes 3 & 6); and the agricultural abandonment process (class 4). On the other hand, cluster 2 has been subdivided into two different classes, as the threshold values in this regional context may represent different situations in terms of the value of the agricultural surface variable, especially on the summit line: class 2a ($\geq$3% agricultural surface) corresponds to stable agro-forestry areas, while class 2b ($\leq$3% agricultural surface) corresponds to a forest degradation process, from tree cover to shrubland ecosystems (Fig. 2).

In the Spanish Central Mountain Range, class 1 (stable forest areas) does not show a spatial correlation with the topography or any other spatial variable, although it is concentrated in the national fire scenario 3 (massifs and forestry ranges). Class 5 (agricultural areas) presents a more disperse or fragmented spatial pattern. In class 2a (agro-forestry areas), considerable surface development can be highlighted, above all in the central sector of the region, as this is an intensely humanized landscape and more sensitive to destabilization processes in terms of wildfire risk.

Contrasting with these areas where human-environment interactions are more stable, shrubland development processes have been identified in relation to agricultural abandonment dynamics (class 4) and forest degradation (class 2b) in the sectors closest to urban zones, which are an indicator of first generation fires. The spread of urban sprawl processes generates areas more sensitive to forest fires, increasing the propensity to fire and the difficulty of its extinction. On the other hand, the forest progression dynamics (classes 3 & 6) representative of second and third wildfire generations, mean landscape homogenization and increased susceptibility to fire risk, related to the extent and severity of forest fires, especially in the provinces of Madrid and Ávila.

The forest tree species parameter is particularly relevant for clusters 1 (stable forest areas) and 6 (expansion of forest areas). Apart from the predominance in terms of surface area of *Quercus ilex* and *Quercus pyrenaica* in this natural region, *Pinus pinaster* and *Pinus sylvestris* are evidently the main tree species in areas with the most intense forest progression. This is a risk factor, depending on the combustibility and flammability of these forest ecosystems (Fig. 3). The forest management map (Fig. 4) shows the highest percentages in the *Quercus* ecosystems and in the *Pinus sylvestris* forests with progression and expansion dynamics, counteracting the wildfire risk in these areas. Also notable is the low level of forest management in the agro-forestry areas and in the *Pinus pinaster* forests of the province of Ávila. Forest management is therefore a key factor of fire regime dynamics and wildfire risk management in the regional context of the Central Mountain Range.

The settlement system of the Central Mountain Range is characteristically concentrated, with urban development on a local scale. Small villages predominate in large rural areas with very low population density. The urban nuclei correspond to the provincial capitals. The wildland-urban interface progression is evident in the NW sector of the Madrid metropolitan region and the urban hinterlands of Ávila and Segovia (Fig. 5).

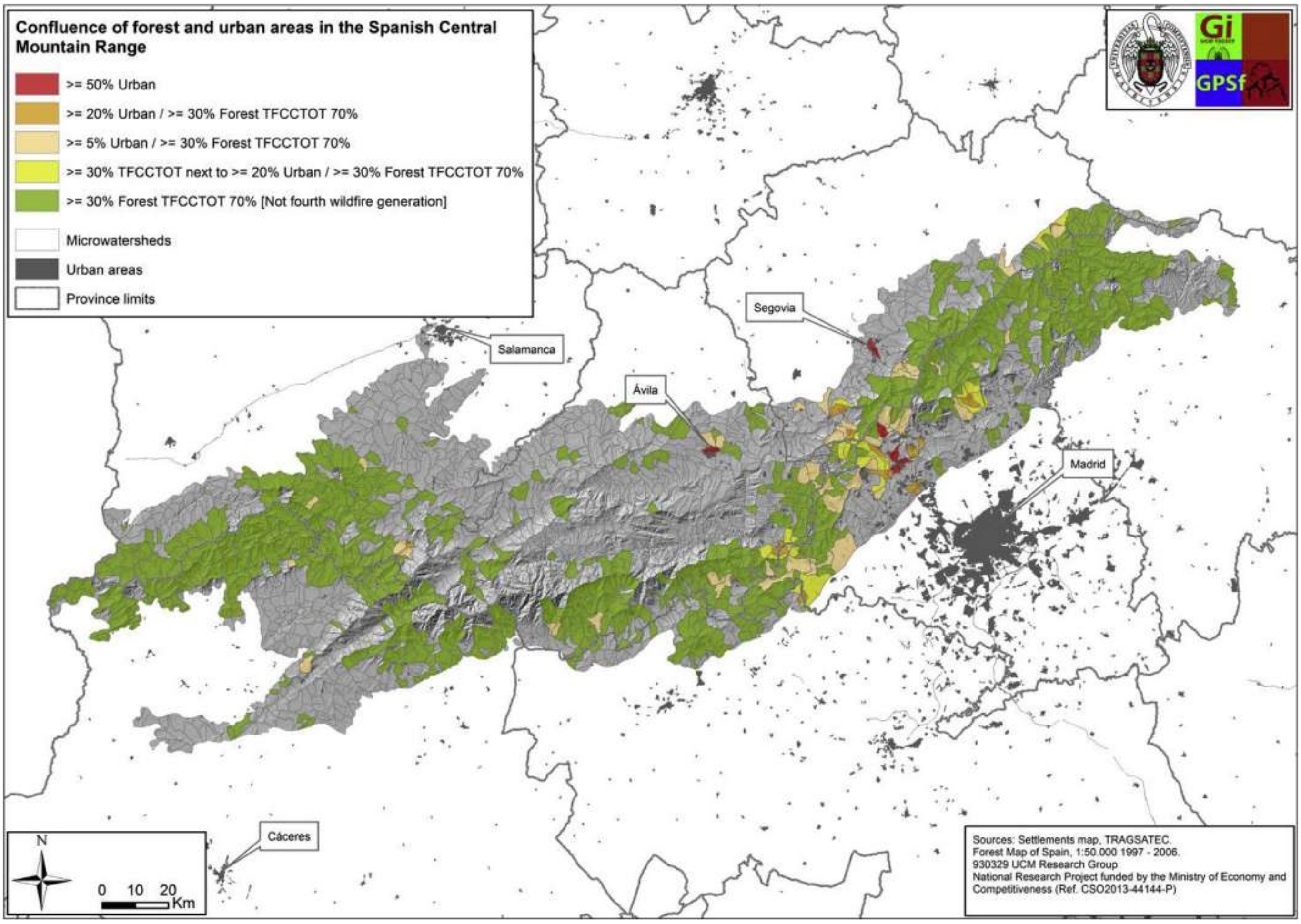


**Fig. 5.** Confluence of forest and urban areas in the Spanish Central Mountain Range.

### *4.2. Delimitation and characterization of land-type fire scenarios*

Landscape dynamics are the basis for defining the regional fire scenarios. The delimitation of these territorial areas which feature shared characteristics in their initial conditions and possible evolution, and the impact of wildfire, is based on a model evolving towards landscapes that favor the development of wildfires which exceed suppression capacity (large wildfires, WUI wildfires and complex simultaneous fires). The degree of agricultural abandonment in relation to cropland is an essential criterion to demarcate areas corresponding to the first wildfire generations. The second and third wildfire generations are mainly linked to a vertical and horizontal fuel continuity due to a progressive abandonment of forest land management. The fourth wildfire generation introduces the urbanization factor into areas of high fuel continuity (Castellnou et al., 2009; Costa et al., 2011; Montiel and Galiana, 2016).

By integrating the spatial variables analyzed, 91 discrete geographic units were differentiated, corresponding to a specific wildfire generation and characterized by a particular LULC (Fig. 6, Table 3). The spatial units identified have been assigned to a specific generation of forest fires depending on the current situation of the fuel structure, paying special attention to the distribution of the variables that inform us of the territorial dynamics in each of the landscape units. Fieldwork and the techniques using geo-visual analysis from aerial photographs have served to confirm the correct assignment of the homogeneous areas thus defined. The net predominance is evident of the regional fire scenarios corresponding to first wildfire generations (type 1), both in number (38 of 91) and above all in surface area (44.5% of the surface area of the Central Mountain Range), as well as in the number and extent of pre-first generation scenarios (20) characterized by greater stability from the point of view of the territorial dynamics and by a lower propensity to large wildfires (Costa et al., 2011). This evidences the late and limited evolution of the territorial dynamics which destabilized the fire regime during the latter half of the 20th century in this inland mountainous region. A strong correlation can also be observed between agricultural areas and more stable landscapes with a less evolved fire regime, concentrated especially in the national scenarios 1 and 4, and corresponding to types 0.a, 0.b, and 0.c. of the regional scenarios. However, these are areas with a rural settlement model and very low population density, which makes them critical regional fire scenarios from the viewpoint of fire management. The pre-first generation regional fire scenarios (type 0) also include one of the landscapes most resilient to fire, which coincides with the protected public forest on the summits of the Guadarrama Massif (class 0.d.). Nevertheless, type 0.d fire scenarios are also the most vulnerable to fire risk in the Central Mountain Range, as they are in direct contact with second generation forestry scenarios (2.a, 2.b, 2.c) and surrounded by wildland-urban interface areas. In addition, most of the forest land forms part of first and second generation fire scenarios which extend W-E over the whole natural region and present a dangerous landscape continuity with the agro-forestry and forest third generation fire scenarios (3.a, 3.b), particularly in the Gata Massif and the Gredos Massif.

In a national context, the Central Mountain Range natural region presents two distinctive features of interest here. First, livestock grazing is the activity which determines the abandonment of pasture land and so the reduction in stock farming density is directly related to the

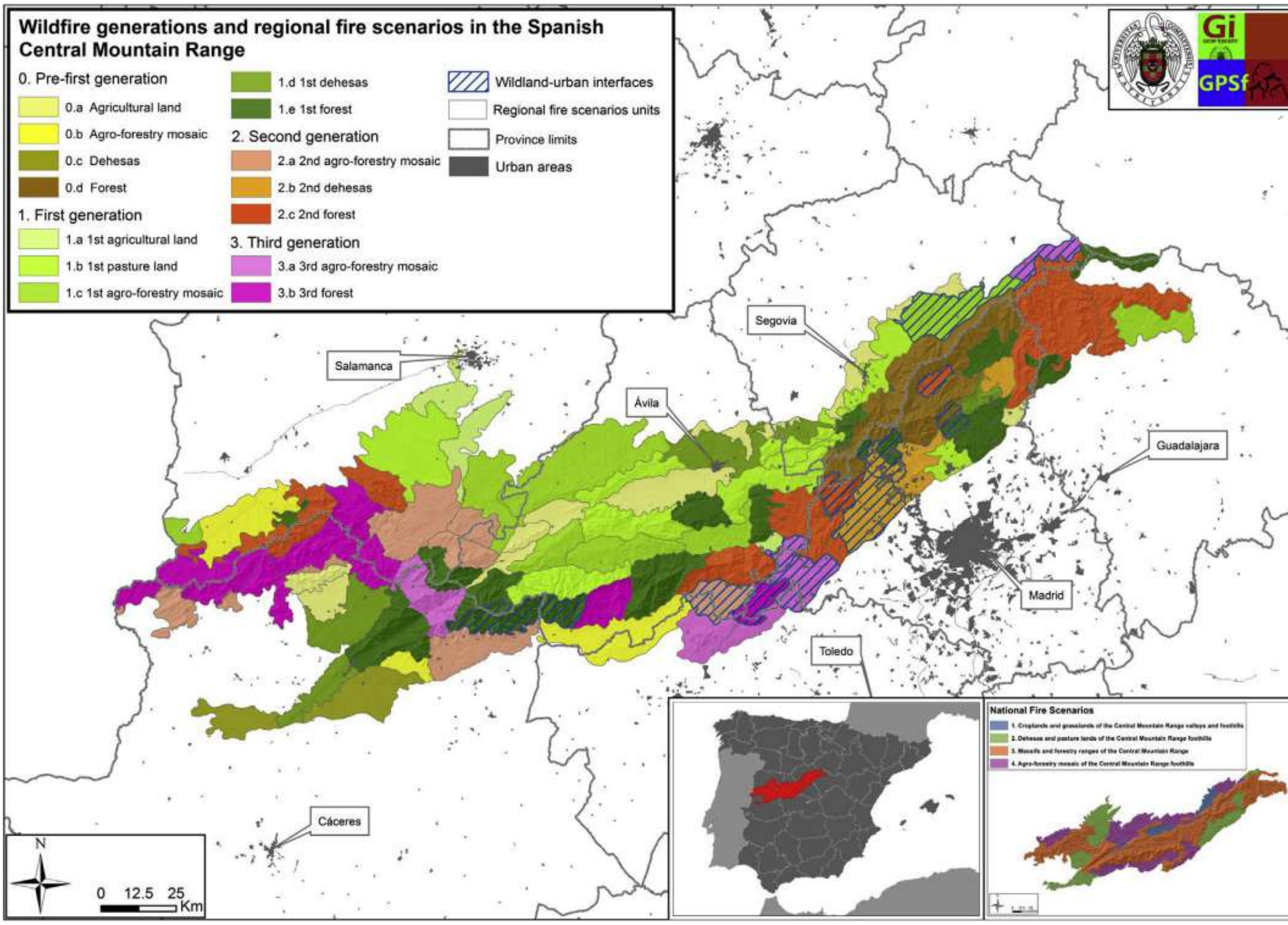


**Fig. 6.** Wildfire generations and regional fire scenarios in the Spanish Central Mountain Range.

**Table 3**
Regional fire scenario typology in the Central Mountain Range.

| Regional Fire Scenarios | | Number of scenarios | Surface (ha) | Percentage of surface (%) |
|---|---|---|---|---|
| 0. PRE-FIRST GENERATION | 0.a. Agricultural land | 10 | 131,155.42 | 6.5 |
| | 0.b. Agro-forestry mosaic | 3 | 77,442.45 | 3.8 |
| | 0.c. *Dehesas* | 1 | 58,010.22 | 2.9 |
| | 0.d. Forest | 5 | 119,978.67 | 5.9 |
| | with wildland-urban interfaces | 1 | 3778.77 | 0.2 |
| | **TOTAL Stable scenarios** | **20** | **390,365.53** | **19.3** |
| 1. FIRST GENERATION | 1.a. Agricultural land | 2 | 45,068.38 | 2.2 |
| | 1.b. Pasture land | 9 | 234,622.77 | 11.6 |
| | 1.c. Agro-forestry mosaic | 7 | 221,015.64 | 11.0 |
| | 1.d. *Dehesas* | 4 | 103,529.86 | 5.1 |
| | 1.e. Forest | 12 | 210,007.55 | 10.4 |
| | with wildland-urban interfaces | 4 | 85,867.81 | 4.2 |
| | **TOTAL 1st generation fire scenarios** | **38** | **900,112.01** | **44.5** |
| 2. SECOND GENERATION | 2.a. Agro-forestry mosaic | 6 | 138,577.93 | 6.9 |
| | 2.b. *Dehesas* | 2 | 30,581.04 | 1.5 |
| | 2.c. Forest | 9 | 240,743.03 | 11.9 |
| | with wildland-urban interfaces | 5 | 83,116.41 | 4.1 |
| | **TOTAL 2nd generation fire scenarios** | **22** | **493,018.41** | **24.4** |
| 3. THIRD GENERATION | 3.a. Agroforestry-mosaic | 3 | 62,773.71 | 3.12 |
| | 3.b. Forest | 4 | 107,458.32 | 5.3 |
| | with wildland-urban interfaces | 4 | 57,104.41 | 2.8 |
| | **TOTAL 3rd generation fire scenarios** | **11** | **227,336.44** | **11.22** |
| **TOTAL** | | **91** | **2,010,832.45** | **100.0** |

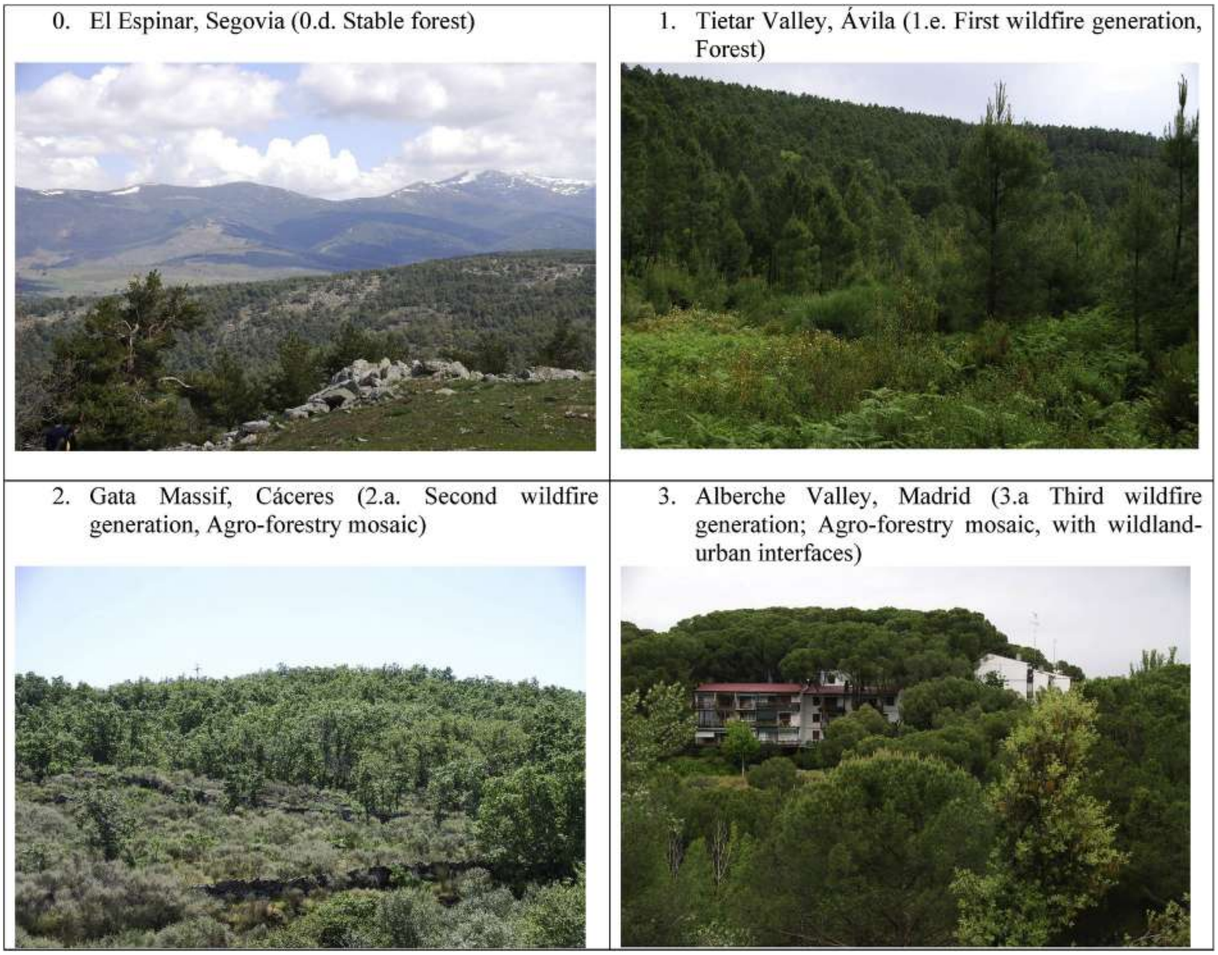


**Fig. 7.** Land-type fire scenarios in the Central Mountain Range.

emergence of first and second generation fire scenarios. In addition, this dynamic particularly affects the agro-forestry mosaics, which are the most complex and conflictive land-type units from a socio-spatial viewpoint. Secondly, fourth generation fire scenarios do not appear in this natural region, as urban sprawl dynamics are not of significant importance at a regional scale in this inland rural area of the Iberian Peninsula. The existing housing developments have led to the configuration of WUI zones, superimposed on all types of wildfire generations, and particularly problematic in the third generation fire scenarios of the Alberche watershed (in the provinces of Madrid and Ávila) but in the end, they do not define any land-type unit characterized by this type of fire regime at a regional scale (50.000–25.000).

The regional fire scenarios identified in the Central Mountain Range demonstrate the complex interactions between landscape dynamics and fire regime (Mermoz et al., 2005; Turner, 2010) which have developed since the mid-20th century as a result of LULC changes and urban sprawl. In some cases these have led to the depopulation and homogenization of the landscape (Varga et al., 2018), but in others have generated a greater fragmentation and complexity of the landscape, and also led to the presence of WUI (Galiana, 2017). In fact, the results obtained lead us to differentiate a series of contrasting territorial situations at a regional scale, depending on the landscape structure and dynamics and which characteristically present challenges and opportunities which are completely different from the wildfire management point of view (Costafreda-Aumedes et al., 2016), as can be seen in the following examples (Fig. 7):

*Regional Fire Scenarios type 0* (El Espinar forest, 0.d.): Most of the surface is covered by officially protected public forest with forest management regulated since the 19th century, which has meant the control of the vegetation dynamics. Additionally, the growth rate of the population and economic activities has been maintained through the 20th century and up to the present day, which has meant that social organization systems and traditional rural land management practices have been maintained. In particular, activities such as stock rearing and extraction of firewood have continued at a local level, which has meant the conservation of ecological structures and fuel control.

*Regional Fire Scenarios type 1* (Tietar Valley, 1.e.): The change of the socioeconomic and lifestyle model in the late 1980s as a result of the decline in resident population and the introduction of tourism, linked to the proliferation of second homes, has meant the dismantling of the sociospatial system and alteration of the ecological equilibrium. Firewood is no longer harvested, and the livestock density has significantly decreased, which has led to densified undergrowth and gradual fuel accumulation affecting the high calorific fire potential causing first generation wildfires.

*Regional Fire Scenarios type 2* (Gata Massif, 2.a.): In a rural setting of complex agro-forest structures, characterized by conflicting historical interests as a result of intensive human occupation, factors such as farming mechanization, abandoning of crop cultivation, decrease in extensive stock rearing and non-maintenance of plot boundaries have all meant increased structural complexity of fuel and loss of the efficiency of spatial discontinuities on fire behavior. The result is the appearance of second generation wildfires and increased uncertainty of the fire spread patterns.

*Regional Fire Scenarios type 3* (Alberche Valley, 3.a. with WUI): The influence of the metropolitan dynamics in the Madrid region on rural areas which have been considerably transformed by age-old human occupation has led to the sudden dismantling of the landscape

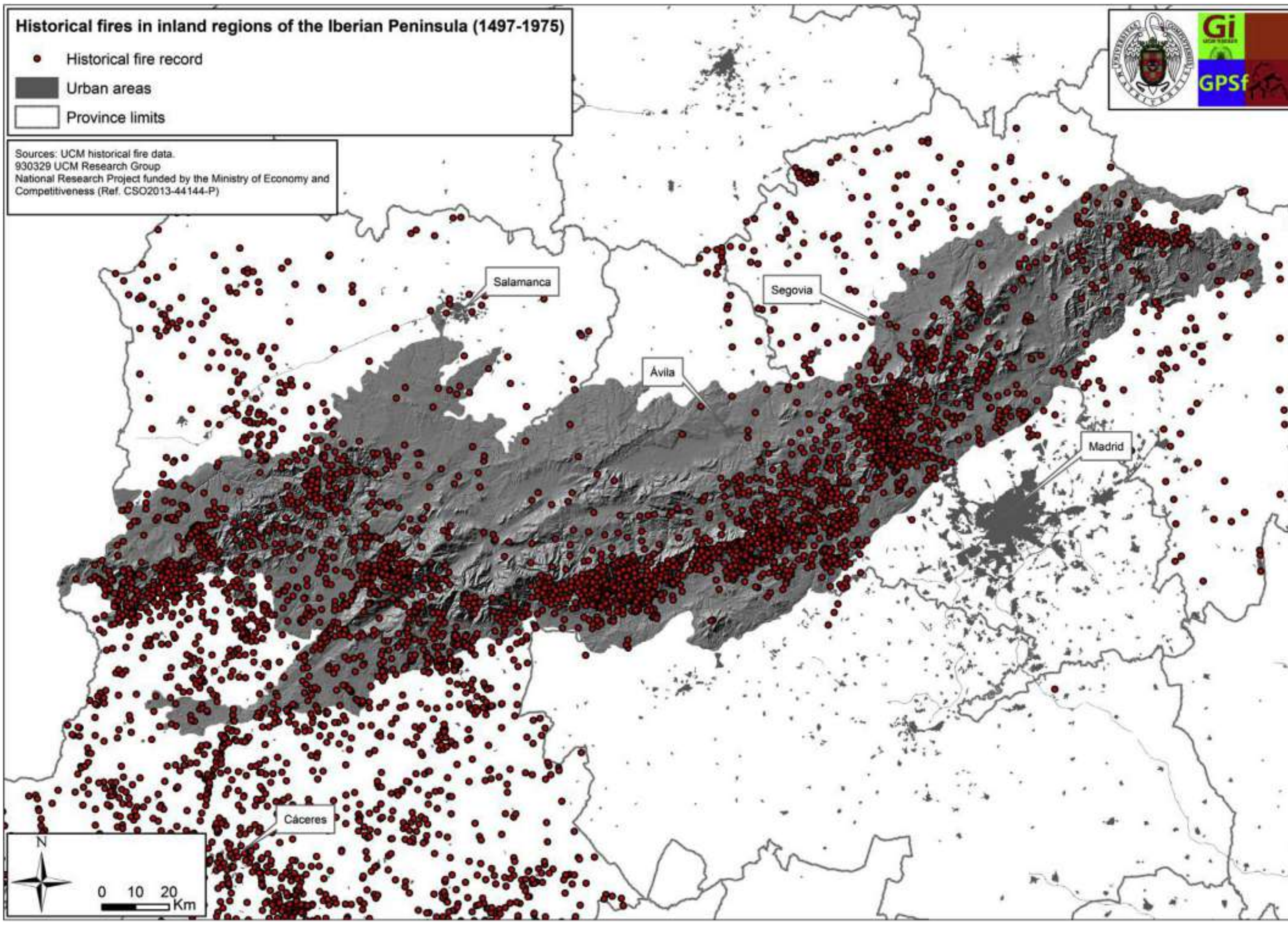


**Fig. 8.** Historical fires in inland regions of the Iberian Peninsula.

structures and the intrusion of occupation types and land management systems more characteristic of urban environments. The abandonment of traditional economic activities and rural land management has destabilized the socioecological system, and simultaneously the WUI expansion has created new risk zones within a framework of uncertainty and maximum vulnerability to wildfire risk.

### *4.3. Applications and operativity of regional fire scenarios for wildfire risk management*

The regional fire scenarios are directly related to the territorial dynamics in the latter half of the 20th century and to the wildfire generations model linked to land management abandonment and urban sprawl processes. However, the regional fire scenarios have not only been configured in relation to recent land use changes, but rather are the outcome of the long-term interaction between fire history and landscape dynamics (Camarero et al., 2018; López-Sáez et al., 2014; Valese et al., 2014). Historical fire records (1497–1975) show a pattern of spatial concentration which mainly coincides with two types of fire scenario: (i) second and third generation forest scenarios (2.c & 3.b) in Gata Massif (Cáceres) and Gredos Massif (Ávila) and the Alberche Valley (Madrid), related to the traditional use of fire as a management tool in rural areas, and also to situations of social conflict on a local scale; (ii) pre-first generation forest scenarios (0.d) in the Guadarrama Massif (Madrid & Segovia), where the records of long series of fires with high frequency, low intensity and limited surface area have enabled the adaptation of the landscape to fire and the formation of resilient landscape structures (Fig. 8). In contrast, recent statistical fires (1998–2013) present a particular pattern of much more disperse and random occurrence, with an outstanding number of fires recorded in the province of Caceres, but with no spatial correlation with current regional fire scenarios (Fig. 9).

Thus, although fire regime changes are related to the territorial dynamics which define the current regional fire scenarios (Moreno and Chuvieco, 2016), these have been configured through a long process of interaction between the fire history and landscape dynamics (López-Sáez et al., 2016; Valese et al., 2014). Additionally, the current wildfire risk is not directly related to the major driving forces which provoked fire regime changes in the more or less recent past, but instead to fire use practices for land management that make up the socioecological systems and to the new lifestyle in the context of global change.

From these considerations, the regional fire scenarios are an effective decision support tool to confront the current challenge of uncertainty management, both in the planning phases and in the organization of pre-suppression tactics, and at the operative point of wildfire management. These land-type units provide added value to predictive models of fire spread patterns (Duane et al., 2015), since they integrate the most relevant information on the foreseeable fire behavior within each landscape context. Their main applications highlight their usefulness for integrating aspects of wildfire risk into spatial planning policies and for adopting preparedness measures within integrated fire management, as they provide an accurate and appropriate spatial framework for land planning and land management for fire hazard reduction.

The regional fire scenarios are also appropriate for balancing fire hazard reduction and conservation of natural resources (Pausas and

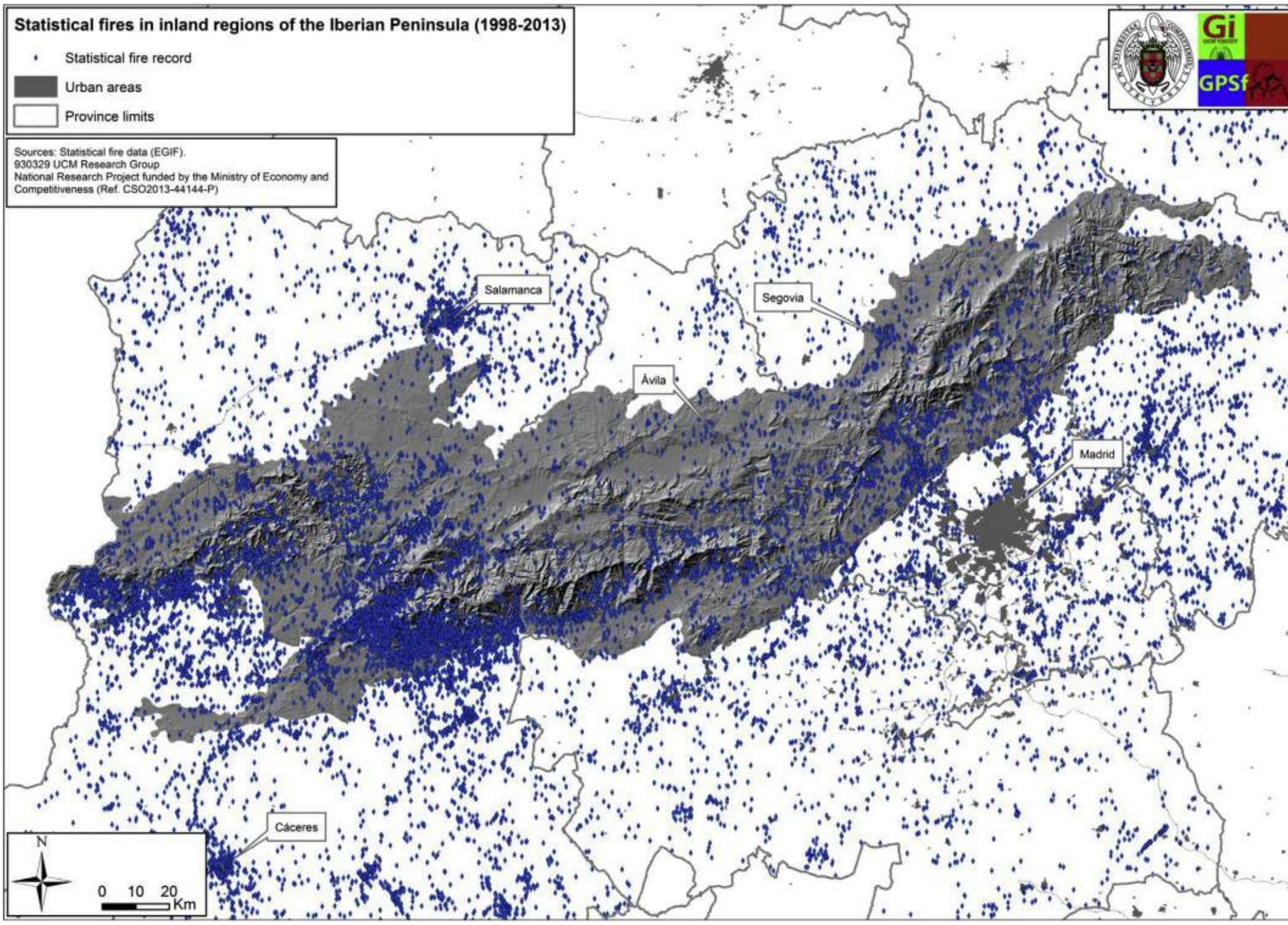


**Fig. 9.** Statistical fires in inland regions of the Iberian Peninsula.

Keeley, 2009). The current priority of forest services usually involves fuel treatment for risk prevention. It means assuming high ecological and economic costs through the loss of environmental goods and services. Furthermore, there is no evidence of the efficiency of fuel treatment actions in terms of reducing natural and human asset loss (Bradstock et al., 2012; Syphard et al., 2014). The real impact and limitations of management actions to reduce fire hazard are currently unknown. In any case, it is essential to differentiate the fuel treatments required in different territorial scenarios for efficient land management. Establishing homogeneous fire regime zones is useful for forest management planning, with the aim of reducing the fire hazard while protecting natural resources.

In addition, there is scale discordance between land management and fire behavior. Whereas fire is a landscape phenomenon, forest management for reducing fire hazard is planned and implemented at the local level. Regional fire scenarios provide the optimal framework to move from a local to a broader scale, by connecting the human and natural systems which define the complex fire problem at the landscape level (Mermoz et al., 2005). This allows for greater effectiveness in fire hazard reduction by treating the coupled natural and human system as a whole, and also by dealing with management objectives at the same scale. In fact, to mitigate wildfire effects, it is essential to focus on changing the landscape into a more tolerant and resistant territorial system. Integrated planning of fire and land management would lead to reduced vulnerability of territories and societies by creating more resilient landscapes.

Finally, it is essential to forecast land-type fire scenarios that minimize fire risk while maintaining biodiversity and protecting human assets in the context of global change. Regional fire scenarios are a tool to integrate fire management and land use planning to reduce the vulnerability of territories and societies (Galiana and Karlsson, 2012). Understanding the dangers inherent in landscape structures is also essential to reduce social vulnerability through adequate preparedness mechanisms adapted to socioecological systems characterization (Paveglio et al., 2018). Thus, regional fire scenarios are framed within the paradigm of living with fire by building up resilient landscapes, adapted communities and proactive policies to address vulnerability problems.

## 5. Conclusions

The regional fire scenarios model aims to establish the spatial differentiation of the structural and dynamic characteristics of a land area in relation to fire behavior. The main outcome of this model is a set of homogeneous areas of landscape/fire interaction providing a context-specific and place-based approach for assessing and interpreting the effects of ecological and socioeconomic factors on fire behavior. This connection between landscape structure and dynamics and fire behavior is essential to move from the current fire management systems based on fire suppression tactics to a more strategical and pro-active fire management approach.

The method defined here to identify the land-type fire scenarios at the regional scale has proved its viability and reliability to adapt the fire policies and land management systems to the current challenges of fire risk territories. We have identified 91 spatial units in the Central Mountain Range corresponding to 18 land-type fire scenarios classes.

These land-type fire scenarios classes are related to the different wildfire generations and land-use areas. The final map of wildfire generations and regional fire scenarios obtained is a useful decision support tool to manage uncertainty at the intermediate spatial scale (between national and local) and with a mid-term planning horizon (1–10 years).

Furthermore, this method can be reproduced in any Mediterranean type region, conditioned only by the availability of data for the variables used, and by the need to adapt the weighting of these variables to the territorial context of each regional situation. In the case study of the Spanish Central Mountain Range, the results obtained have enabled improvements to the efficacy and safety of extinction systems and for reducing the social and territorial vulnerability to catastrophic wildfires.

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## Declarations of interest

None.

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