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# Analyzing the recent dynamics of wildland fires in *Quercus suber* L. woodlands in Sardinia (Italy), Corsica (France) and Catalonia (Spain)

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## Abstract

Wildland fires represent a major threat to *Quercus suber* L. ecosystems, which provide relevant socio-economic and ecological services in the Mediterranean Basin. In this work, we analyzed recent wildland fire dynamics in cork oak woodlands along the fire-prone areas of Sardinia (Italy), Corsica (France), and Catalonia (Spain). We first characterized geographic extent and main characteristics of cork oak woodlands in these regions and analyzed how environmental (climate and elevation) and socio-economic factors (population and land uses) vary in the areas covered by *Quercus suber* L. We then evaluated how wildfires affected cork oak stands and, by logistic regression analysis, to what extent wildfires in cork oak areas were related to the above set of environmental and anthropic explanatory variables. Results revealed specific variations across study areas in cork oak characteristics as well as in environmental and social factors. We highlighted the spatial and temporal patterns of wildfires on cork oak woodlands, in terms of extent, seasonality, frequency, and main driving factors. In the period 2003-2015, the percentage of cork oak woodlands burned ranged from 3.42% in Corsica to 11.30% in Sardinia. A few large and severe wildfires accounted for most of the area burned in cork oak woodlands. The most significant predictive variable that explained the spatial variation in wildland fire ignitions inside or nearby cork oaks was summer precipitation, while the weight of other factors varied depending on the region. This study provides evidence on recent fire dynamics in cork oak woodlands and gives valuable information and insights for the implementation of forest management and planning strategies in the Mediterranean area.

## Keywords

Cork oaks, Mediterranean Basin, fire regime, fire management, land management

## 1. Introduction

Cork oak (*Quercus suber* L.) is a long-lived (up to hundreds of years) evergreen tree, endemic to the Mediterranean basin (EEA 2007). Cork oak woodlands are mostly concentrated in a few Mediterranean countries and cover about 2.2 million hectares (FAO 2013). The area of *Quercus suber* L. in Europe is estimated to be close to 1.5 million hectares, the majority of which located in the Iberian Peninsula (FAO 2013; Dettori and Filigheddu 2016). The high presence of *Quercus suber* L. in the Mediterranean Basin is linked to its high economic and cultural value for rural communities (Urbieta *et al.* 2008; FAO 2013; Corona *et al.* 2018): cork is the second most important marketable non-wood forest product in the western Mediterranean Basin, with annual world cork market exports close to € 1.45 billion (Aronson *et al.* 2009; Catry *et al.* 2012a; APCOR 2016). *Quercus suber* L. stands have been intensively managed, protected and shaped by human activities over millennia for the nutritional values of acorns, to provide shelter and shade for livestock, and for the production of wood for domestic uses. In addition, cork oak forests supply a number of other goods and ecosystem services, including habitats for many animal species and plant endemisms, leisure activities, tourism, beekeeping, aromatic herbs, or edible mushrooms. The social-ecological values that humans have imprinted on cork oak environments in the Mediterranean Basin generated unique cultural landscapes, which in turn influence local and regional culture and identity (Aronson *et al.* 2009; Plieninger *et al.* 2014). The landscape, cultural and ecological value of cork oak areas is also acknowledged in the Natura 2000 Network by the European Commission (DG Environment 2007).

As other Mediterranean forest systems, a number of previous studies have reported that cork oak ecosystems are in decline or endangered. The spatial distribution and vitality of *Quercus suber* L. woodlands are affected by several complex and sometimes interrelated disturbance factors (Luciano and Roversi 2001; Dettori and Filigheddu 2003, 2016; Silva and Catry 2006; EEA 2007; Pereira 2007; Acacio *et al.* 2009; Bugalho *et al.* 2011; FAO 2013; Oubrahim *et al.* 2015; Acha and Newing 2015; Oliveira *et al.* 2016; Dettori *et al.* 2018). Wildland fires represent one of the most relevant disturbances for cork oaks, as well as for other forests in the Mediterranean Basin. Nonetheless, it is widely accepted that fires are an integral part of the dynamics of many forest ecosystems, as they play a fundamental role in forest renewal and on insect and disease control (FAO 2013, Moritz *et al.* 2014). In Europe, forest fires mainly affect the Southern areas: in the period 2000-2015, about 51,000 fires per year have been recorded, burning approximately 380,000 ha of land (San-Miguel-Ayanz *et al.* 2016). In the Mediterranean Basin, most of the ignitions have anthropogenic origin, while area burned and fire intensity are primarily determined by weather conditions, topography, fuel load and continuity (Romero-Calcerrada *et al.* 2008; Pausas and Paula 2012; Ager *et al.* 2014b; Oliveira *et al.* 2014; Levin *et al.* 2016; San-Miguel-Ayanz *et al.* 2016; Turco *et al.* 2017; Rodrigues *et al.* 2018). Climate change is expected to increase future wildfire risk, area burned and the frequency of high severity events all over Southern Europe (Moriondo *et al.* 2006; Lung *et al.* 2013; Bedia *et al.* 2014; Kovats *et al.* 2014; Lozano *et al.* 2017). Furthermore, climate change can exacerbate stress conditions related to droughts, heat waves, pests and diseases, thereby contributing to the potential decline of cork oak woodlands in the next decades (Bergot *et al.* 2004; Luciano *et al.* 2005; Catry *et al.* 2012a; Costa *et al.* 2014). The recent trends of forest, agricultural and livestock activity abandonment, as well as the changes in the domestic energetic sources and the afforestation of abandoned lands, are responsible for the increase in highly flammable fuel accumulation and continuity, with potential effects on fire regime (Bonet and Pausas 2007; Baeza *et al.* 2011; Pausas and Fernandez-Munoz 2012; Madrigal *et al.* 2016). These factors could further increase the vulnerability to wildland fires of Mediterranean forests in future decades (Moreira *et al.* 2011; Salis *et al.* 2016b; Alcasena *et al.* 2016a).

*Quercus suber* L. is considered a fire-resistant and fire-resilient plant, due to its stem and crown resprouting capability (through epicormic buds), even after intense crown fires, and to the thick bark that ensures protection and insulation to the cambium from the heat produced by fires. Therefore, cork oaks are very competitive in the post-fire recovery phases in comparison to several other species (Pausas 1997; Curt and Pausas 2010; Catry *et al.* 2012a). For this reason, summer fires, even induced by landowners, have favored the expansion of cork oaks in Sardinia at the expense of *Quercus ilex* L. and *Quercus pubescens* Willd. (Vogiatzakis and Careddu 2003). However, there is evidence that post-fire cork oak response and recovery capabilities may largely vary depending on several factors such as bark thickness, debarking interval, tree diameter, fire intensity and spread rate (Pausas 1997; Barberis *et al.* 2003; Moreira *et al.* 2007; Catry *et al.* 2009, 2012b). Moreover, an important issue for burned cork oaks is that the bark often becomes unsuitable for the most profitable industrial uses for a long period, which results in important economic losses to forest and rural communities. Hence, the incidence and effects of wildland fires on cork oak stands in the Mediterranean area are highly relevant to land managers, planners, and policymakers, according to the strategic economic, ecological and cultural importance of the *Quercus suber* L. woodlands.

In this work, we investigated the recent wildland fire dynamics on cork oak stands in three Mediterranean regions, namely Sardinia (Italy), Corsica (France), and Catalonia (Spain), where *Quercus suber* L. woodlands cover approximately 265,000 ha (about 18% of the European cork oak surface area). This research addresses the limited knowledge on recent wildfire trends in cork oak areas and on the geographic distribution of *Quercus suber* L. in the areas under investigation. The main research questions of this work are: (1) What are the main geographic, environmental and socio-economic characteristics of the areas covered by *Quercus suber* L. woodlands? (2) To what extent have wildfires threatened cork oaks? (3) Do environmental and socio-economic factors explain the historical wildfire incidence in *Quercus suber* L. woodlands? The answers to these questions provide insights and data on wildland fire dynamics that can support the implementation of forest management strategies and policies specific for cork oak forests.

## 2. Materials and Methods

### *2.1. Study areas*

The study was conducted in the fire-prone regions of Sardinia (Italy), Corsica (France), and Catalonia (Spain), located in the north-western part of the Mediterranean Basin (Fig. 1). For this study, we used “region” and “province” as reference terms to identify NUTS-2 and NUTS-3 levels (EU Classification of Territorial Units for Statistics) for the study areas. The main characteristics of these areas are summarized in Table 1.

**Table 1.** *Summary of the main characteristics of the study areas. The sources of this information are provided in the next sub-sections*

| | **Sardinia (Italy)** | **Corsica (France)** | **Catalonia (Spain)** |
|---|---|---|---|
| *Size (km$^2$)* | 24,100 | 8,700 | 32,100 |
| *Inhabitants* | 1.65 M | 0.33 M | 7.50 M |
| *Population* | mostly concentrated nearby the main towns of Cagliari and Sassari | mostly concentrated nearby the main towns of Ajaccio and Bastia | mostly concentrated in the metropolitan area of Barcelona and the coastal areas |
| *Climate Type* | hot-summer Med.; warm-summer Med. above 750 m a.s.l. | hot-summer Med.; warm-summer Med. above 500 m | hot-summer Med.; warm-summer Med. in NW Catalonia; from cold-summer |

| | | | |
|---|---|---|---|
| | | a.s.l.; cold-summer Med. above 1,500 m. a.s.l. | Med. until alpine above 1,200 m a.s.l. |
| *Annual Precipitation* | from ~400 mm in the southern coasts to ~1,100 mm in the mountain areas | from ~500 mm in some coastal areas to more than 1,100 mm in the mountain areas | from ~400 mm in the inner areas of Lleida to more than 1,500 mm in the Pyrenees areas |
| *Mean Annual Temperature* | from ~7 °C in the mountain areas to ~17 °C along the southern coasts | from ~3 °C at the highest elevations to ~16 °C in the coastal areas | from ~0 °C in the Pyrenees to ~17 °C in the southern coasts |

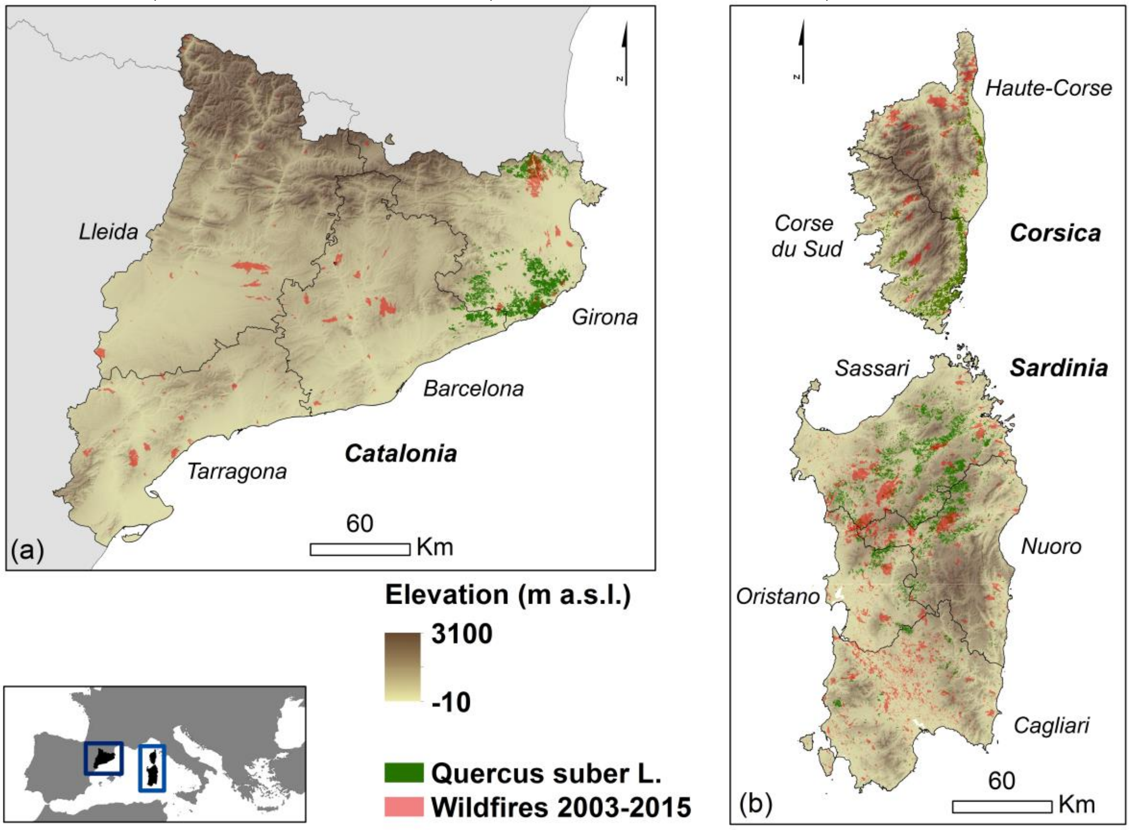


***Fig. 1**. Digital elevation model (DEM) of the study areas (Catalonia, a; Sardinia and Corsica, b), along with the spatial distribution of Quercus suber L. woodlands (green polygons) and the administrative NUTS-3 boundaries (provinces of Cagliari, Sassari, Nuoro and Oristano in Sardinia; provinces of Barcelona, Tarragona, Girona, and Lleida in Catalonia, departments of Corse du Sud and Haute-Corse in Corsica) used for the present study. The perimeters of the wildland fires (red color) that affected the study areas in the period 2003-2015 are also shown.*

In the period 2003-2015, the total area burned in the study area was about 218,000 ha in Sardinia, 65,000 ha in Corsica and 61,000 ha in Catalonia; the average area burned per year was about 17,000 ha in Sardinia, 5,000 ha in Corsica, and 4,700 ha in Catalonia (Fig. 1 and Suppl. Fig. 1). The worst fire seasons in terms of total area burned (more than 30,000 ha) were observed in 2003 (Corsica), and in 2007 and 2009 (Sardinia). Overall, in the study period wildland fires affected less than 4% of the provincial areas in Catalonia as well as in Southern Corsica (Suppl. Fig. 1). Northern Corsica and Cagliari provinces were the most affected by fires (respectively 11.5% and 10.4% of the provincial areas in the 13-years study period). The highest provincial area burned by year was observed in Northern Corsica (6.1%) in 2003, Sassari (2.8%) in 2009, and Nuoro (2.3%) in 2007 (Suppl. Fig. 1). A peak in burned area was observed in July for all provinces, except for Tarragona (May), Northern Corsica and Barcelona (August) (Suppl. Fig. 2).

## *2.2. Data compilation*

### *2.2.1. Cork oak woodland data*

The *Quercus suber* L. woodlands data for the study areas were derived from the most accurate spatial input data available at national or regional levels. In Sardinia, the information source was the "Land Use Map of Sardinia" (2008), which is a polygon shapefile that maps the Sardinian land uses with minimum mapping unit of 0.75 ha (www.sardegnageoportale.it). The information of this database is hierarchically organized following the CORINE Land Cover classification at the fifth level. The codes associated with cork oaks are: 2.4.1.3 (Annual crops associated with permanent crops (pastures and grasslands with *Quercus suber* L. cover below 25%) and 3.1.1.2.2 (*Quercus suber* L. forests). The spatial location of cork oak woodlands in Corsica was derived from the "Inventaire Forestier National 2003" (https://inventaire-forestier.ign.fr/, minimum mapping unit of 20 ha). The map has three specific categories related to cork oak: *Quercus suber* L. forests, Mediterranean maquis with *Quercus suber* L., mixed *Quercus suber* L. woodlands and coppice. The cork oak information for Catalonia was obtained from the "Pure and Mixed Forest Type Map of Catalonia" (Vericat *et al.* 2010, minimum mapping unit of 25 ha). The classes associated to cork oaks, or to areas where cork oaks are the dominant forest types, are the following: a) *Quercus suber* L. forests; b) *Quercus suber* L. and other Quercus spp.; c) *Quercus suber* L. and Pinus spp.; d) *Quercus suber* L. and other species.

### *2.2.2. Wildland fire data*

We gathered the perimeters of the wildland fires that affected Sardinia, Corsica, and Catalonia for the study period 2003-2015. These data were provided by regional forest administrations: the Sardinia Forest Service (CFVA), the Office National de Foret (ONF), and the Generalitat de Catalunya (GenCat), for Sardinia, Corsica and Catalonia, respectively. We then merged and, in the case of unclosed polygons, rectified (about 0.01% of the data series) the wildland fire perimeters and the associated databases. Furthermore, we collected a longer time series (1990-2015) of wildland fire occurrence to analyze the spatial and temporal patterns of fire ignitions in the study areas. The ignition data of Catalonia were obtained from MAGRAMA (Spanish Ministry of Agriculture, Food and Environment), while for Sardinia and Corsica the data were provided by CFVA and ONF. We first checked the fire databases to evaluate their consistency, and we encountered a certain number of records (about 25%), particularly in the period 1990-2002, where ignition points coordinates were missing or incorrectly reported. In these cases, we randomly distributed the fire ignitions within municipalities. We then used the ignition point database to derive reference raster maps (100-m resolution) of historical ignition point densities for the periods 1990-2002 and 2003-2015. A radius search distance of 5,000 m was set to generate smoothed maps of historical ignition density. This distance has been found significant in other works (i.e. Vega-Garcia *et al.* 1995), and compensates for possible errors in the ignition point coordinates of the historic databases.

#### *2.2.3. Other input data*

Terrain elevation information for the study areas was obtained from the EU-DEM data provided by the EEA (2017b). The EU-DEM is a 25-m resolution digital terrain model (DTM), and covers the whole EU countries plus some neighboring areas. Climate conditions of the study areas and of the cork oak stands were derived from the 1-km resolution "WorldClim version 2" database (Fick and Hijmans 2017), which provides monthly climate data for the period 1970-2000. Population density data at municipality level for the study areas were gathered from the Italian, French and Spanish census data, and refer to the years 1990, 2000 (1999 for Corsica) and 2010. Finally, we used the Corine land cover data (CLC, years 1990, 2000, and 2012, EEA 2017a) to analyze temporal variations in land use patterns for the study areas. The CLC data are seamless vector coverages of land covers for several European countries, with a minimum mapping unit of 25 ha. The CLC classification consists of an inventory of 44 land cover classes, grouped in a three-level hierarchy. In this work, we focused our attention on the following classes: artificial surfaces (codes 111, 112, 121, 122, 123, 124, 131, 132, 133, 141, 142), arable land (211, 212), permanent crops (221, 222, 223), heterogeneous agricultural areas (241, 242, 243, 244), forests (311, 312, 313), scrub and/or herbaceous vegetation associations (321, 322, 323, 324).

### *2.3. Data analysis*

#### *2.3.1 Geographic extent and environmental and socio-economic conditions in the cork oak areas*

To characterize *Quercus suber* L. areas, we first mapped the cork oak woodlands and determined their total extent at provincial and regional levels while taking into account elevation classes and climate conditions. For terrain elevation, we used 250-m as reference range to discriminate the cork oak distribution in the study areas as a function of the elevation. We then applied the non-parametric Kruskal-Wallis statistical test to evaluate the significance of differences ($p$ = 0.05) among provinces. Regarding climatic conditions, we computed average, minimum and maximum values of temperatures and total precipitation at the provincial level and on the areas covered by cork oak woodlands, using as temporal reference: 1) the months from June to September (which essentially represent the fire season in the majority of the study areas); and 2) the annual averages. We then applied the Kruskal-Wallis test to evaluate the significance of differences ($p$ = 0.05) in climatic conditions among provinces. To evaluate demographic and land use variations from 1990 to 2010 in the cork oak zones of the study areas, we selected municipalities characterized by a presence of *Quercus suber* L. woodlands above 5% of the total municipality area (Suppl. Fig. 3, and Fig. 2 and 3).

#### *2.3.2 Historical trends in wildfires on cork oak areas*

We intersected wildland fire perimeters and cork oak woodlands polygons to quantify the hectares of *Quercus suber* L. burned at provincial and regional scales in the period 2003-2015. Moreover, we determined the cork oak area burned by year and by month in the study areas. The role played by the size of historical wildland fires (using as reference three size classes: ≤ 1 ha; 1-10 ha; 10-100 ha; > 100 ha) on cork oak area burned in the period 2003-2015, at the regional and provincial levels, was also investigated. We then evaluated the distance between ignition locations of large wildland fires and *Quercus suber* L. woodlands polygons by using the "Near" command of ArcGIS 10.3. For this purpose, we used 100 ha as a threshold to identify large events. The analysis was carried out considering two reference periods (2003-2015 and 1990-2002) and three reference distance classes (< 1 km, 1-10 km, and >10 km).

#### *2.3.3 Relationships between wildfire occurrence in cork oaks and environmental and socio-economic factors*

We applied logistic regression to analyze, at the regional scale, the relationships between the 1990-2015 wildland fires ignited inside or in the proximity of cork oak woodlands (using a 1-km buffer area around the *Quercus suber* L. polygons) and the following explanatory environmental and socio-economic variables: climate, topography, population density, and land use. We rasterized the explanatory variables using a reference grid of 5-km resolution for the whole study areas and quantified the number of annual fire ignitions for each cell. The logistic regression was used for binary classification (presence/absence) of fire ignitions inside the cork oak grid cells. The estimates of the binary response probability were based on the values of the explanatory variables. The final multivariate models were obtained by using a stepwise approach and considering all possible combinations of the variables for each region. The null hypothesis (the effects of the explanatory variables in the logistic models are equal to zero) was tested by the p-value of the Wald Chi-Square statistics. The Wald statistic was also used to evaluate the significance of both intercept and predictors used in the models. We evaluated the adequacy of the fitted models by the Hosmer and Lemeshow (2000) test, a Pearson Chi-Square statistic that reflects the differences between observed and expected probabilities and provides an estimate of the lack of fit (p = 0.01). In addition, the association between observed and predicted data was measured by the c-statistic (Bamber 1975), which is the percentage of pairs with concordant prediction and is commonly used as a standard measure of the predictive accuracy of a logistic regression model. C-statistic values were used to compare the different models, considering that c values range from 0.5 (random classification) to 1 (perfect association). We used the overall model accuracy to test the improvement determined by the use of explanatory variables over the intercept-only model.

## 3. Results

### *3.1. Characterizing geographic extent and environmental and socio-economic conditions of the cork oak areas*

As shown in Table 2 and Fig. 1, the presence of *Quercus suber* L. woodlands differs at the provincial level. Sardinia has about 138,400 ha of lands covered by cork oak (5.75% of the regional territory), while in Corsica the area covered by cork oak woodlands is around 64,500 ha (7.40% of the regional territory) (Table 2). On the other hand, *Quercus suber* L. woodlands encompass only about 1.91% (approximately 61,400 ha) of Catalonia (Table 2), and are only present in the northeastern zone of this region (Barcelona and Girona provinces).

***Table 2***. *Summary of the Quercus suber L. woodlands extension (in hectares) for the study areas. The relative percentage of provincial and regional area is reported under parenthesis. The surface area is rounded to the nearest ten.*

| **Cagliari** | **Sassari** | **Nuoro** | **Oristano** | **SARDINIA** |
|---|---|---|---|---|
| 9,030<br>*(1.19%)* | 80,430<br>*(10.46%)* | 35,880<br>*(6.20%)* | 13,090<br>*(4.33%)* | 138,430<br>*(5.75%)* |
| **Corse du Sud** | **Haute-Corse** | | | **CORSICA** |
| 46,570<br>*(10.95%)* | 17,930<br>*(4.01%)* | | | 64,500<br>*(7.40%)* |
| **Barcelona** | **Girona** | **Tarragona** | **Lleida** | **CATALONIA** |
| 7,910<br>*(1.02%)* | 53,480<br>*(9.06%)* | - | - | 61,390<br>*(1.91%)* |

In Sardinia, the northern province of Sassari accounts for about 60% of the Sardinian cork oaks woodlands, while in Corsica *Quercus suber* L. woodlands are mainly present in Corse du Sud (46,570 ha) (Table 2). Catalonian *Quercus suber* L. woodlands are widespread in the province of Girona, which accounts to about 87% of the overall regional cork oak area (Table 2). Considering the distribution of cork oaks at the provincial level, Corse du Sud, Sassari and Girona show the highest presence of *Quercus suber* L. woodlands, which cover more than 9% of the provincial area. Cork oak woodlands account for 4-6% of the provincial territory in Nuoro, Oristano, and Haute-Corse, while their incidence in the other provinces is very limited (Cagliari and Barcelona) or null (Tarragona and Lleida) (Table 2).

Concerning the analysis of the cork oak stands at different elevation classes, the study areas show statistically significant differences (Table 3). *Quercus suber* L. woodlands are located at elevations much above the average provincial elevation in Cagliari and Oristano (376 m vs. 227 m a.s.l. and 350 m vs. 210 m a.s.l., respectively), while in Corsica and Catalonia they grow in areas below or largely below the average provincial elevation. In Corsica, more than 80% of *Quercus suber* L. woodlands is located in the 0-250 m elevation class (Table 3). Also in Catalonia the presence of cork oaks is most important at 0-250 m elevation class (about 60% of the total area), while only 33% of the Catalonia cork oak woodlands is found at 250-500 m altitude. The presence of cork oaks at elevations above 500 m is less than 5% of the regional and provincial areas of Catalonia and Corsica (Table 3). In Sardinia, about 50% of the *Quercus suber* L. stands are located at 250-500 m altitude class, with a relevant presence also at the 500-750 m elevation class (26% vs. less than 3% for Catalonia and Corsica). In the provinces of Nuoro and Cagliari, cork oaks woodlands at elevations above 500 m represent about 55% and 40% of the provincial cork oak area, respectively. There are no significant statistical differences in average elevation of cork oak woodlands between Catalonian provinces, as well as for Cagliari, Oristano, and Sassari provinces (Table 3).

***Table 3****. Average terrain elevation (ELEV), average elevation of cork oak woodlands (ELEV QS), and percentage distribution of Quercus suber L. woodlands at different terrain elevation classes (0-250; 250-500; 500-750; >750 m a.s.l.) in the provinces of the study areas. The Kruskal–Wallis test (p = 0.05) was performed to evaluate statistical differences in average elevation and average elevation of cork oak woodlands among provinces. Different letters in the same column indicate significant differences among provinces at p = 0.05.*

| PROVINCE | ELEV (m) | ELEV QS (m) | 0-250 | 250-500 | 500-750 | >750 |
|---|---|---|---|---|---|---|
| Cagliari | 227.1f | 376.3b | 24.08 | 36.54 | 38.84 | 0.54 |
| Nuoro | 526.1b | 504.4a | 12.32 | 32.57 | 41.37 | 13.74 |
| Oristano | 210.9g | 350.0b | 14.08 | 75.49 | 10.36 | 0.07 |
| Sassari | 325.7e | 394.7b | 22.39 | 55.33 | 20.00 | 2.28 |
| Corse du Sud | 560.4a | 159.4e | 87.51 | 12.13 | 0.36 | 0.00 |
| Haute-Corse | 592.3a | 201.7d | 69.07 | 28.30 | 2.48 | 0.15 |
| Barcelona | 518.1c | 251.2c | 68.78 | 29.14 | 2.07 | 0.00 |
| Girona | 517.2d | 243.6c | 60.08 | 34.05 | 5.16 | 0.71 |

The average climatic conditions of *Quercus suber* L. woodlands at the provincial level are provided in Table 4. Overall, the climate of these areas is quite similar, particularly at the annual time lag (i.e.: average temperatures range approximately from 14.9 °C in Oristano to 14.1 °C in Nuoro). When taking into account only the June-September period, the ranges of some climatic variables in the *Quercus suber* L. woodlands show to be larger, particularly the average accumulated precipitation (i.e.: from 76.4 mm in Cagliari to 232.9 mm in Barcelona) and the average maximum temperature (from 26.1 °C in Corse du Sud to 28.9 °C in Oristano) (Table 4). The maps of average maximum temperatures and accumulated precipitation observed in the study areas during the period June-September are presented in the Suppl. Fig. 4 and 5.

***Table 4****. Average mean temperature (TAVG, in °C), minimum temperature (Tm, in °C), maximum temperature (TM, in °C), and accumulated precipitation (PP, in mm), at the annual level and for the period June-September, in the areas covered by Quercus suber L. woodlands. The results are summarized at the provincial level.*

*Climate data were obtained from the 1-km resolution "WorldClim version 2" data (Fick and Hijmans 2017). The Kruskal–Wallis test (p = 0.05) was performed to evaluate statistical differences in climate conditions of cork oak woodlands among provinces. Different letters in the same column indicate significant differences at p = 0.05.*

| | YEAR | | | | JUNE-SEPT | | | |
|---|---|---|---|---|---|---|---|---|
| **PROVINCE** | ***T*** | ***Tm*** | ***TM*** | ***PP*** | ***T*** | ***Tm*** | ***TM*** | ***PP*** |
| Cagliari | 14.8b | 10.6e | 19.0b | 624.2e | 21.6b | 16.5d | 28.6b | 76.4f |
| Nuoro | 14.1e | 10.3f | 17.9g | 716.4b | 21.1d | 16.4e | 27.8c | 90.4d |
| Oristano | 14.9a | 10.8d | 19.1a | 728.0b | 21.8a | 16.7c | 28.9a | 83.9e |
| Sassari | 14.5c | 10.8d | 18.3d | 703.5c | 21.3c | 16.7c | 27.8c | 88.1d |
| Corse du Sud | 14.9a | 11.8a | 18.1e | 612.7e | 21.0e | 17.4b | 26.1f | 91.8d |
| Haute-Corse | 14.5d | 11.0c | 18.0f | 663.6d | 20.7f | 16.7c | 26.3e | 113.1c |
| Barcelona | 14.9ab | 11.4b | 18.4c | 761.4a | 21.6b | 17.8a | 26.9d | 232.9a |
| Girona | 14.7bc | 11.0c | 18.4cd | 726.7b | 21.3c | 17.3b | 26.9d | 214.1b |

The variations in population density in the municipalities where the presence of *Quercus suber* L. woodlands is above 5% of the municipality area are reported in Fig. 2, which is summarized at the regional level. Overall, the population in Corsica and Catalonia increased between 1990 and 2010 by 22% and 39%, respectively, with the highest variation observed in the province of Barcelona (+48%). On the contrary, in the same period we observed a decrease of about 5% of the inhabitants in the main cork oak areas of Sardinia, particularly in the inner lands. In addition, while in Catalonia and Corsica the percent change in population from 1990 to 2010 was quite uniform at the provincial level, Sardinia showed uneven changes: the province of Sassari exhibited slight changes and average variations close to zero, while the decrease in population in the main cork oak areas was over 11% in Cagliari and Oristano, and close to 10% in Nuoro.

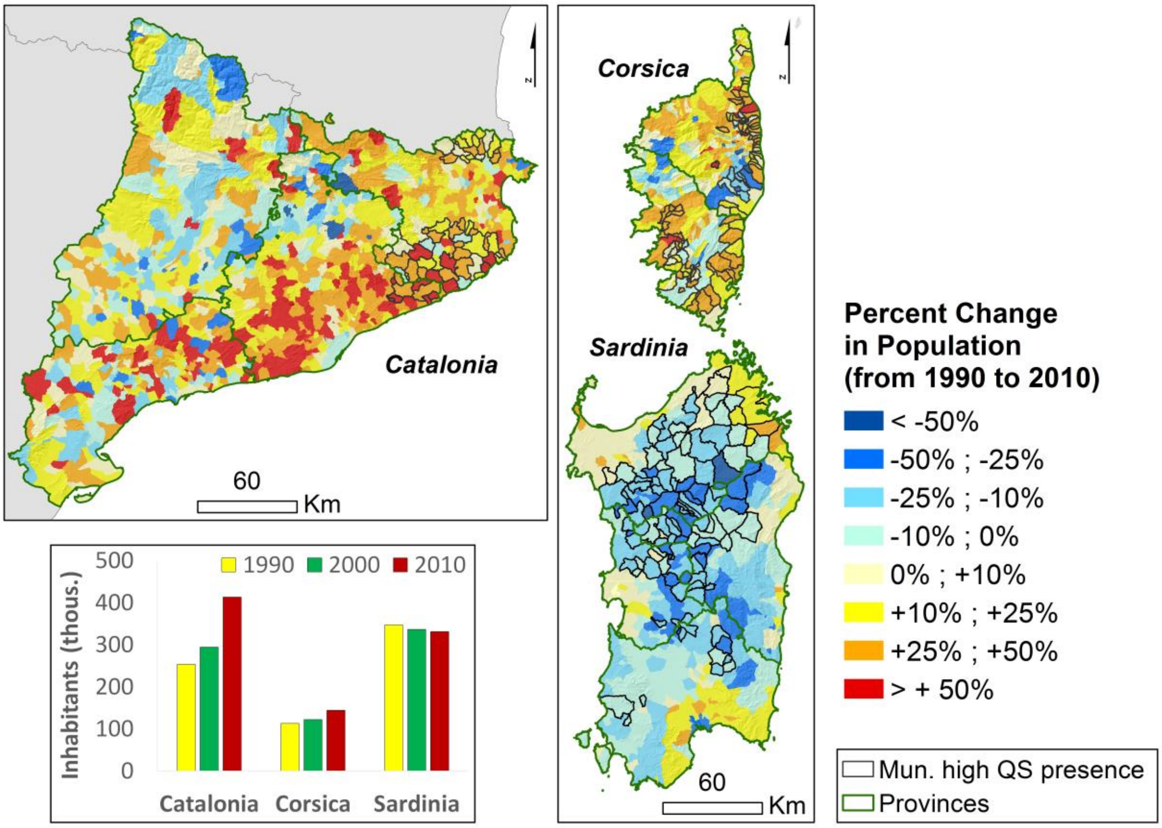


***Fig. 2***. *Map of the percent change in population between 1990 and 2010 in the study areas. The histograms report the number of inhabitants in the municipalities characterized by a presence of Quercus suber L. woodlands above 5% of the municipality area. The population data refer to census data of 1990, 2000, and 2010.*

As for changes in main land uses between 1990 and 2012 in the municipalities characterized by a presence of *Quercus suber* L. woodlands above 5% of the municipality area (Fig. 3), we observed an overall increase in the surface areas covered by forests (particularly relevant in Catalonia) and artificial surfaces. Scrubs and herbaceous vegetation decreased in the study areas, with particular relevance in Catalonia and Sardinia. Concerning the other land uses, the variations were more complex and did not follow a common trend (Fig. 3).

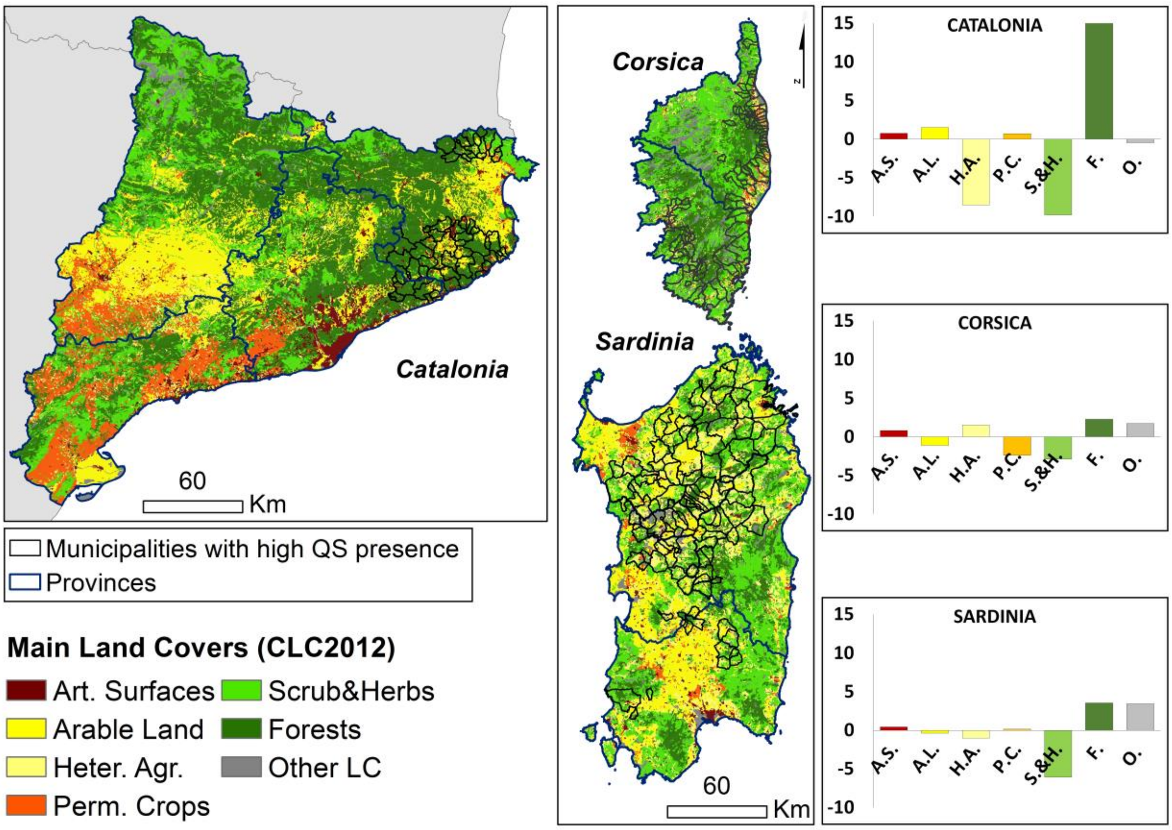


***Fig. 3***. *Map of the main land covers of the study areas according to Corine Land Cover 2012 (CLC2012). The histograms report the percent variations between CLC2012 and CLC1990 of the main land covers for the municipalities characterized by a presence of Quercus suber L. woodlands above 5% of the municipality area. A.S. = artificial surfaces; A.L. = arable land; H.A. = heterogeneous agricultural areas; P.C. = permanent crops; S.&H. = scrubs and herbs association; F. = forests; O. = other land covers.*

### *3.2. Evaluating the wildfire trends in cork oak areas*

In the study period 2003-2015, the total cork oak woodland area burned in the regions under investigation was around 23,500 ha (Fig. 1). Sardinia accounted for about 66% of the total cork oak area burned. In this island, on average about 1,200 ha of *Quercus suber* L. stands (about 0.87% of the regional cork oak area) were burned each year (Fig. 4). In the 13-years study period, the total Sardinia cork oak area burned was about 15,500 ha. The worst seasons for *Quercus suber* L. woodlands were observed in 2007 and 2009, with about 2.79% (≈ 3,850 ha) and 3.23% (≈ 4,450 ha), respectively, of the total cork oak area burned. In Corsica (Fig. 4), only 3.42% (≈ 2,200 ha) of the regional area covered by *Quercus suber* L. stands was burned in the study period. This means that, on average, the annual cork oak area burned was about 165 ha, that is 0.26% of the total Corsica cork oak area. Furthermore, the annual percentage of *Quercus suber* L. woodlands burned over the total area covered by cork oaks was always less than 1%. In Catalonia, about 9.38% (≈ 5,700 ha) of the area covered by *Quercus suber* L. woodlands was burned, with an annual average of 0.72% (about 450 ha) (Fig. 4). Nearly 7.5% (≈ 4,400 ha) of the Catalonia *Quercus suber* L. woodland area was burned in 2012 and was almost entirely concentrated in the province of Girona (Fig. 4). Overall, the combination of wildland fire and cork oak woodland shapefiles in Sardinia, Corsica and Catalonia revealed that the *Quercus suber* L. areas which burned more than once in the period 2003-2015 were limited and ranged from 0 to less than 1% of the total cork oak area burned at the provincial level.

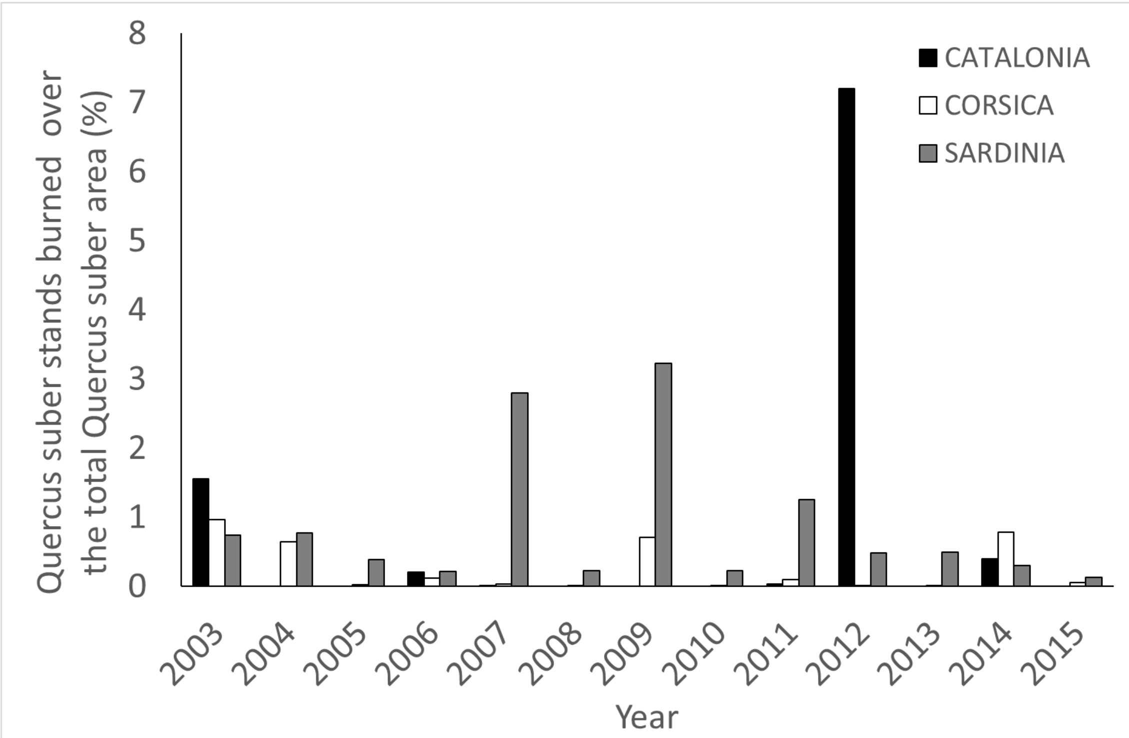


***Fig. 4***. *Quercus suber L. woodlands area affected by wildland fires vs. regional cork oak area for Catalonia, Corsica and Sardinia, for the study period 2003-2015.*

A small number (< 2%) of large fire events (> 100 ha) accounted for most of the total cork oak area burned at the regional scale. The role played by large fires in *Quercus suber* L. woodlands burned was very significant in Catalonia (about 99% of the total cork oak burned determined by large events), while in Corsica and Sardinia they accounted for about 79% and 72%, respectively, of the total *Quercus suber* L. area burned (Table 5). This analysis highlighted some relevant differences also at the provincial level. For instance, the most relevant variation in the role played by the different fire size class was observed in Sardinian provinces. In fact, while in Sassari and Nuoro provinces the large fires (> 100 ha) accounted for more than 75% of the total cork oak area burned, in southern Sardinia these events were responsible for about 31% of the *Quercus suber* L. burned, and the highest contribution to cork oak area burned was due to the fire size class 10-100 ha (Table 5). Corsica also presented marked differences: large events accounted for about 88% of the total *Quercus suber* L. woodlands burned in Haute Corse, and for about 64% in Corse du Sud. In Catalonia, in both Girona and Barcelona provinces, the fire size class >100 ha caused more than 98% of the total cork oak area burned. A single forest fire event (Suppl. Fig. 6a) played a key role in determining the cork oak losses in Catalonia and particularly in

Girona province. Specifically, on July 2012, the largest Catalonian wildland fire (La Jonquera, about 10,500 ha) of the period 2003-2015 burned approximately 4,100 ha of *Quercus suber* L. woodlands, corresponding to about 94% of the total cork oak area burned in that year, and to about 72% of the total cork oak area burned in the region over the 13 years of reference. Another example of the significant role played by large events is represented by the wildland fire of Nuoro (Suppl. Fig. 6b) in Sardinia. This event (about 9,000 ha), which was the largest Sardinian wildland fire of the summer season 2007, burned approximately 2,600 ha of *Quercus suber* L. woodlands, which represent about 67% and 17% of the total cork oak area burned in 2007 and during the study period, respectively.

***Table 5.*** *Percentage of Quercus suber L. woodlands burned by wildland fire size class (≤ 1 ha; 1-10 ha; 10-100 ha; > 100 ha), for the period 2003-2015, at the regional and provincial levels.*

| | **Percentage of QS burned by wildfire size class** | | | | |
|---|---|---|---|---|---|
| **Province / Region** | **≤1 ha** | **1-10 ha** | **10-100 ha** | **>100 ha** | **TOTAL** |
| Cagliari | 2.75 | 18.17 | 48.21 | 30.86 | 100.00 |
| Nuoro | 0.49 | 7.36 | 15.15 | 77.01 | 100.00 |
| Oristano | 0.78 | 14.56 | 20.80 | 63.85 | 100.00 |
| Sassari | 0.61 | 8.21 | 17.13 | 74.05 | 100.00 |
| **Sardinia** | **0.67** | **8.94** | **17.94** | **72.45** | **100.00** |
| Corse du Sud | 1.17 | 5.13 | 29.36 | 64.34 | 100.00 |
| Haute Corse | 0.84 | 4.76 | 6.08 | 88.31 | 100.00 |
| **Corsica** | **0.97** | **4.91** | **15.41** | **78.71** | **100.00** |
| Barcelona | 0.00 | 0.00 | 0.00 | 100.00 | 100.00 |
| Girona | 0.00 | 0.00 | 1.32 | 98.68 | 100.00 |
| **Catalonia** | **0.00** | **0.00** | **1.28** | **98.72** | **100.00** |

In Catalonia and Sardinia, *Quercus suber* L. woodlands were mostly affected by fires in July (more than 65% of the total cork oak area), followed by August (with about 13% and 19% of the total cork oak area burned in Corsica and Sardinia, respectively) (Fig. 5). The cork oak area burned in July was about 10,550 ha in Sardinia and 4,200 ha in Catalonia (concentrated in the province of Girona). However, in Sardinia, relevant differences in the monthly distribution of the cork oak burned were observed: in the northern provinces of Sassari and Nuoro, about 90% of the cork oak stands burned in July and August, while in the other two provinces the wildfires occurred in these months accounted for about 75% of the total *Quercus suber* L. area burned. Also in Corsica, July was the month with the highest percentage (about 39%) of *Quercus suber* L. woodlands burned, but a relevant percentage (about 22%) of the cork oak woodlands burned was also observed in August and October (Fig. 5). The Corsican provinces presented large differences in the monthly distribution of the cork oak burned: in Corse du Sud, about 73% of the total cork oak area burned was concentrated in July, while in Haute Corse the peak (about 87%) was observed in August-October.

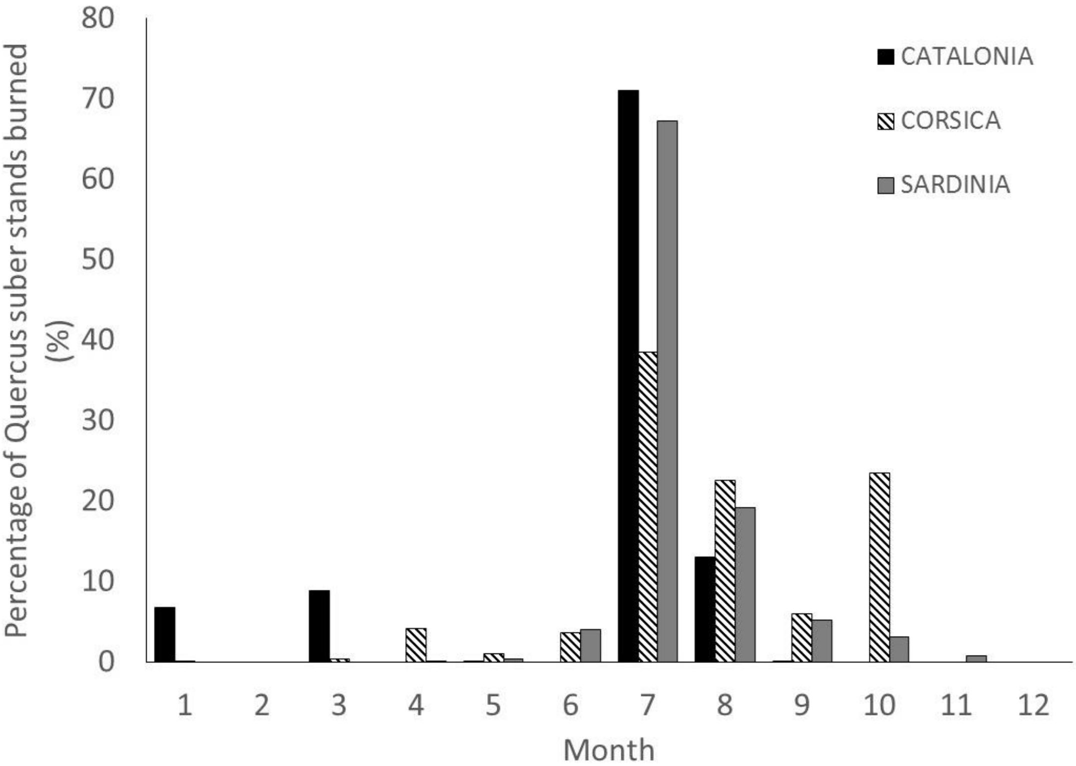


***Fig. 5***. *Percentage of the monthly distribution of the Quercus suber L. woodlands area affected by fires in Catalonia, Corsica, and Sardinia, for the study period 2003-2015.*

The relation between the wildland fire ignition locations and the distance to cork oak stands was analyzed considering the reference period 2003-2015 and the previous 13-year timeframe (1990-2002). Fig. 6 highlights the spatial variations in large fire event (> 100 ha) location and ignition point densities between the two periods. On the whole, the fire ignition point density dropped from 1990-2002 to 2003-2015 for most of the study areas, the main exception being south-western Sardinia (Fig. 6), which showed more areas with peaks above 8 fire ignitions km$^{-2}$ in the period 2003-2015. Moreover, large fire (>100 ha) number and area burned decreased considerably in the study areas moving from the first to the second period (Fig. 6). For instance, the number of large fires dropped to 289 events (vs. 541 in the period 1990-2002) in Sardinia, to 47 (vs. 113) in Corsica, and to 75 (vs. 116) in Catalonia. The analysis of the percentage of fire ignition locations as function of the distance from cork oak woodlands and provinces for both 1990-2002 and 2003-2015 revealed that from the first to the second period, wildland fires ignited in the vicinity (< 1 km) of cork oak woodlands areas tended to decrease, except in the province of Girona (Suppl. Table 1). In the period 2003-2015, the likelihood of fire ignitions at the distance class 0-1 km from *Quercus suber* L. woodlands was over 40% of the total ignitions in the provinces of Girona, Nuoro, and Sassari, while Cagliari and Barcelona provinces showed values below 15%. The province of Barcelona presented the largest distances between fire ignitions and cork oak areas (Suppl. Table 1).

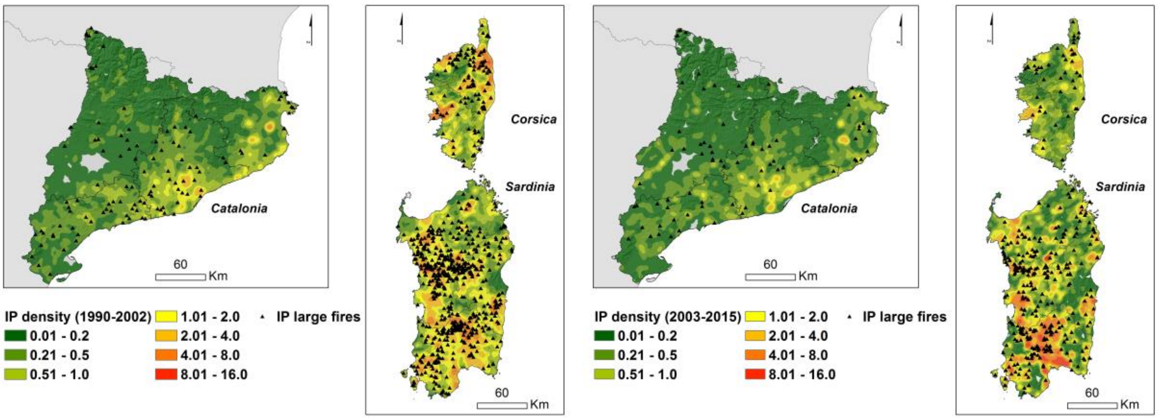


***Fig. 6***. *Maps of the historic ignition point density (in # / km$^2$) of the periods 1990-2002 (left) and 2003-2015 (right) for the study areas. The ignition point density was calculated using the Point Density tool of ArcGIS (ESRI) and a radius search distance of 5,000 m. The black triangles indicate the ignition point location of the large wildland fire events (>100 ha) that affected the study areas for the above periods.*

### *3.3. Analyzing the relationships between wildfire occurrence in cork oak areas and environmental and socio-economic factors*

The driving variables that mostly affected wildland fire ignitions inside and nearby (1-km buffer) cork oak areas at the regional scale were identified by a set of logistic regression models (Table 6). The Catalonia model was not statistically significant according to the Wald test, while the Sardinia and Corsica models resulted highly statistically significant (p = 0.01). However, the Corsica and Sardinia models exhibited a significant lack of fit according to the Hosmer & Lemeshow test (Table 6). Overall, the models showed values of correct classification between 55% and 73%, with the highest values observed in Corsica. C-statistic values range from 0.73 (Sardinia model) to 0.79 (Corsica and Catalonia models), and thus indicated an overall good predictive accuracy of the logistic models (Table 6). In the study areas, the most significant predictive variable that explained the spatial variation of wildland fire ignitions inside or nearby cork oaks was summer precipitation. In more detail, for both Sardinia and Corsica, the most significant predictive variables of the logistic models were land use classes (Anthropic and Agricultural Areas), population density, elevation and summer precipitation (Table 6). As far as climatic conditions are concerned, we also found a major effect of summer maximum temperatures in Sardinia and summer average temperatures in Corsica. Slope played a significant role for the Sardinia model. In Catalonia, the spatial variation of fire ignitions inside or nearby cork oak areas was mainly explained by climatic conditions, namely summer precipitation and annual precipitation (Table 6).

***Table 6.*** *Significance of the variables that affected wildland fire ignitions inside and nearby (1-km buffer) cork oak areas as provided by logistic regression models, considering the study period 1990-2015. The values of the coefficient estimates, the Wald Chi-Square values and the significance of the Chi-Square statistics are reported for each predictive variable. Regarding land uses, the main land use classes are reported if significant. ELEV = elevation; SLO = slope; TMAXS = average summer maximum temperatures; TMS = average summer mean temperatures; PRECS = average summer precipitation; PREC = average annual precipitation; POP =*

*population density; LU = land uses. WCF = Wald test coefficient; HLCF = Hosmer & Lemeshow test coefficient; CORR = percentage of correct estimates; c = c-statistic value. *** = p < 0.01; ** = p < 0.05; n.s. = not significant*

| | | **Sardinia** | **Corsica** | **Catalonia** |
|---|---|---|---|---|
| **Predictive variables** | **ELEV** | -0.005 (190.7)*** | 0.03 (43.04)*** | n.s. |
| | **SLO** | 0.06 (10.32)** | n.s. | n.s. |
| | **TMAXS** | -1.22 (470.5)*** | n.s. | n.s. |
| | **TMS** | n.s. | 7.58 (43.04)*** | n.s. |
| | **PRECS** | 0.01 (5.65)*** | 3.62 (-0.03)*** | -0.03 (3.00)*** |
| | **PREC** | n.s. | n.s. | -0.11 (3.91)** |
| | **POP** | 0.006 (83.41)*** | -0.005 (9.95)*** | n.s. |
| | **LU** | Agricultural -0.01***<br>Anthropic -0.33 (30.6)*** | Agricultural -2.29***<br>Anthropic 4.11 (10.46)*** | n.s. |
| **Model performance parameters** | **WCF** | 862*** | 122*** | 11 n.s. |
| | **HLCF** | 35.95*** | 33.20*** | 16.91 n.s. |
| | **CORR** | 67.2 | 73.0 | 55.4 |
| | **c** | 0.73 | 0.79 | 0.79 |

## 4. Discussion and Conclusions

The main goal of this work was to analyze the recent wildland fire dynamics on cork oak areas in Sardinia (Italy), Corsica (France), and Catalonia (Spain). We aimed to provide answers to the following research questions: (1) What are the main geographic, environmental and socio-economic characteristics of the areas covered by *Quercus suber* L. woodlands? (2) To what extent have wildfires affected cork oaks? (3) Do environmental and socio-economic factors explain the historical wildfire incidence in *Quercus suber* L. woodlands?

The study areas encompass about 265,000 ha of *Quercus suber* L. woodlands, about 18% of the European cork oak surface area. Our study showed relevant differences in the spatial distribution of cork oaks in the regions under investigation. The presence of cork oak stands is mainly concentrated in the provincial areas of Corse du Sud, Sassari and Girona: these provinces account for more than 50% of the regional *Quercus suber* L. woodlands. Previous studies (Dettori and Filigheddu 2003; Pereira 2007; FAO 2013) have pointed out that the differences in cork oak extent within provinces and regions depend upon several interrelated factors, among which the most relevant are climatic conditions, income and jobs related to the cork industry, pressure of pastoral and agricultural activities, and urban sprawl. Our work showed that the climatic conditions in the cork oak woodlands of the study areas were relatively similar, but for summer precipitation and summer average maximum temperatures. This could explain the high presence of cork oak woodlands at elevation classes > 500 m a.s.l. in Sardinia, while in Corsica and Catalonia *Quercus suber* L. areas are largely concentrated at the lowest elevation classes (< 250 m a.s.l.). Differences in climatic conditions would also explain why Sardinian cork oaks are located at higher elevations than in Corsica and Catalonia. Drought conditions and the increasing extent and role played by agricultural expansion could further explain the limited presence of cork oaks in southern Sardinia, or their absence in Tarragona and Lleida provinces.

The variation in population density between 1990 and 2010 assumed distinct patterns across regions. While at the regional level most Corsican and Catalonian municipalities presented, save from a few localized inner areas, a general increase in population density, Sardinia showed a large decline of population density in municipalities far from coastlands and main towns. The population density decline observed in the cork oak areas of Sardinia can be related to a combination of socio-economic issues, including unemployment, abandonment of rural and forest activities, ageing population, low birthrates, distance to main services and towns, and low incomes, which led to emigration of young people towards coastal areas and towns, or even outside, as observed in other Mediterranean areas (Romero-Calcerrada and Perry 2004; Figueredo and Raschi 2011; Kerckhof *et al.* 2016; Forleo *et al.* 2017). For land use variation from 1990 to 2012, we observed an increase in forests and artificial surfaces and a reduction in shrublands in the municipalities covered by large extensions of cork oak woodlands for Sardinia, Corsica and Catalonia. The highest increase in forest areas (about 15%) in the vicinity of cork oak polygons was observed in Catalonia, followed by Sardinia and Corsica (about 2-4%). These variations suggest that cork oaks or other forest types are gradually occupying areas previously covered by shrublands and marginal rangelands, with a potential increase in fuel load and continuity, particularly in the zones where population density is decreasing and vegetation succession is leading to scrub encroachment and new forest development (Arianotsou 2001; Scozzafava and De Sanctis 2006; Moreira *et al.* 2011). In addition, the increased presence of artificial surfaces in the municipalities covered by large areas of cork oak woodlands indicates an expansion of urban interfaces in the wildlands.

We found that in the study areas approximately 23,500 ha of cork oak stands (about 9% of the total *Quercus suber* L. woodlands) were affected by wildland fires in the period 2003-2015. Sardinia accounted for about 66% of the cork oak woodland area burned. Evident interannual variability in the cork oak area burned was observed. Overall, the percentage of cork oak woodlands burned at least once ranged from 3.42% in Corsica to 11.30% in Sardinia for the study period 2003-2015. The highest cork oak area burned observed in Sardinia could be partially explained by the higher presence of herbaceous fuels and dehesas, which can favor the quick spread of large wildland fires under strong wind conditions (Salis *et al.* 2018). The role played by environmental factors on burned area in the Mediterranean Basin has been explored in previous works. There is evidence that a small number of large fires spreading with extreme weather conditions is responsible for the majority of the area burned during a fire season, and that containment activities have minor effectiveness on fire growth during these events (Pereira *et al.* 2005; Koutsias *et al.* 2012; San Miguel-Ayanz *et al.* 2013; Alcasena *et al.* 2016b; Salis *et al.* 2016a). Large wildland fires often exhibit extreme behavior (i.e., high intensity, crown fire activity and spotting fire emission) and can produce damaging impacts on human life, assets and activities as well as severe disturbances to forest ecosystems. Our work confirms that wildland fires greater than 100 ha, which accounted for 1-2% of the total number of wildland fires, were associated to most of the area burned in *Quercus suber* L. woodlands in the study areas, except for southern Sardinia. For instance, in the study period, about 70% of the cork oak woodlands in Catalonia burned in a single fire event (La Jonquera, final size about 10,000 ha), and more than 90% of the La Jonquera fire area burned at high or very high severity (severicat.ctfc.cat). Similar findings were observed in Sardinia during the 2007 and 2009 fire seasons when extreme weather conditions and simultaneous wildland fires concentrated in a few days overwhelmed fire suppression capabilities and burned large portions of cork oak areas in the provinces of Nuoro and Sassari.

The present study also reveals that both the number of fire events and the area burned by wildland fires bigger than 100 ha, which are the primary drivers of fire regime in cork oak landscapes in the study areas, decreased considerably from 1990-2002 to 2003-2015, and that overall the distance between fire ignitions and cork oak woodlands areas increased. Furthermore, we observed an overall reduction of fire ignitions from 1990-2002 to 2003-2015 for almost the entire study areas, the main exception being in southern and western Sardinia. This is in line with previous studies that analyzed wildland fire trends in the Mediterranean Basin (Turco *et al.* 2016; Jimenez-Ruano *et al.* 2017; Curt and Frejaville 2018). The fact that large wildland fires impacting cork oak areas dropped in recent years can be explained by the improvements in fire monitoring and suppression capabilities, by the reduction in fire ignitions related to agro-pastoral causes, and by a general shift of both people and fire ignitions towards coastal and main residential areas (Viedma *et al.* 2006; Chas-Amil *et al.* 2013; Salis *et al.* 2014; Curt and Frejaville 2018). Some studies emphasized that fire exclusion policies can substantially increase the vulnerability of many dry forests to uncharacteristically extensive and severe perturbations, particularly from wildfire and insects/disease, due to their emphasis on short-term outcomes (reducing annual area burned and fire ignitions) vs. long-term goals (promoting more resilient landscapes and forests) (Piñol *et al.* 2005, 2007; Calkin *et al.* 2015; Stephens *et al.* 2016; Camia *et al.* 2017; Curt and Frejaville 2018; Thompson *et al.* 2018). These issues pose severe threats for fire management in future years in the study areas, since the reduction in forest management activities, in conjunction with the limited occurrence of small-size and low severity fires in cork oak areas, and the decrease in population in inner areas such as seen in Sardinia, could promote the accumulation of unmanaged high-load fuels, the expansion of ladder fuels, and the increase in fuel connectivity. This can lead to more fire-prone landscapes in the Mediterranean area, to a potential increase in the likelihood of extreme behavior and severe wildland fire events, thus able to spread further and increase in size, and to more limitations for effective fire suppression of aerial and terrestrial forces (Moreno *et al.* 1998; Pausas and Vallejo 1999; Pausas and Fernandez-Munoz 2012; Salis *et al.* 2013; Ferreira-Leite *et al.* 2016). Therefore, it is likely that, in future years, wildland fires affecting forest areas will start increasingly far from the woodlands and will impact the forest stands after spreading for long distances, thus resulting in an overall increase of the so-called mega-fires, as dramatically observed in the European summer season 2017 (San-Miguel-Ayanz *et al.* 2013; Viegas *et al.* 2017). High-intensity wildland fires could ultimately trigger substantial changes on cork oak forest structures from old-growth forests with a commercial interest to post-fire shrubby coppices, which require long-time and expensive restoration efforts. Consequently, specific management strategies including fuel treatments should be planned and carried out by policy makers and land managers to reduce potential losses from future wildland fires in the Mediterranean Basin, in order to preserve important natural ecosystem heritages like the cork oak forests. A number of works highlighted that surface fuel reduction, silvicultural treatments, and better-planned land mosaics could significantly decrease fire risk in cork oak areas (Baeza *et al.* 2006; Santana *et al.* 2011; Catry *et al.* 2012b; Schaffhauser *et al.* 2012; Curt *et al.* 2013; Salis *et al.* 2016b, 2018). This brings to light the need for integrating large fire spread analysis and fire risk transmission with the design of appropriate wildfire management strategies, particularly for protecting highly valued areas or habitats of endangered species (Ager *et al.* 2014a, 2017; Alcasena *et al.* 2017, 2018a; Thompson *et al.* 2017; Salis *et al.* 2016b, 2018). Prevention and protection strategies may also involve prescribed burning action and may allow the spread of low-intensity wildland fires when weather conditions are mild, in agreement with the proactive concept of integrated fire management (Molina *et al.* 2010; Fernandes *et al.* 2013; Montiel Molina and Galiana-Martín 2016; Alcasena *et al.* 2018b).

We observed that the highest cork oak area burned was concentrated during the months of July and August, which in Catalonia and Sardinia accounted for almost 80% of the total *Quercus suber* L. area affected by fires. Summer months are typically the hottest and driest of the year in the Mediterranean Basin (Flohn and Fantechi 1984). This confirms the key role of drought conditions, and particularly of dead and live fuel moisture, in the dynamics of fire regimes in Mediterranean Europe (Piñol *et al.* 1998; Moreira et al. 2011; Turco *et al.* 2017). From this point of view, the logistic regression analysis performed in the study areas demonstrated that climatic factors, namely summer and annual precipitation, and maximum and average summer temperatures, were significantly related to wildland fire ignitions nearby cork oak woodlands. Furthermore, summer precipitation was a key driving factor in determining wildfires nearby cork oaks for the three study areas. The fact that wildfires occurring in dry years tend to burn larger areas than in wet years was also observed in other European fire-prone areas, as for instance in the Valencia region of Spain (Pausas 2004), in Portugal (Viegas and Viegas 1994), and in Greece (Dimitrakopoulos *et al.* 2011; Xystrakis *et al.* 2014). Moreover, our study indicates that, while in Catalonia fire ignitions in the vicinity of cork oaks are mainly explained by summer and annual precipitation, Corsica and Sardinia showed more complex patterns: in these regions, elevation and land use play a significant role, together with population density and some climate variables. These results support the fact that, even if wildfire ignitions in Mediterranean areas are mostly determined by anthropic factors, a significant component of the variability in wildfire occurrence is explained by climatic conditions (Pausas 2004, Pereira *et al.* 2013). For these reasons, predicted climate change is likely to affect future fire dynamics in *Quercus suber* L. woodlands. With a higher frequency of extreme weather conditions, fire-prone landscapes can be increasingly vulnerable and able to sustain high-intensity and uncontrollable fire events, which can negatively affect cork oak postfire recovery (Fernandes and Rego 1996; Baeza *et al.* 2006; Pausas and Paula 2012; Schaffhauser *et al.* 2012). In addition, under the predicted changes in climate conditions, cork oak ecosystems could be potentially replaced by more xeric species and pyrophytic shrublands and could shift northward or to higher elevations (Costa and Madeira 2011; Costa *et al.* 2014; Ibáñez *et al.* 2017; Varela 2017).

In conclusion, the cork oak woodlands of the study areas represent an important portion of the European *Quercus suber* L. ecosystems and a significant ecological, cultural, and economic heritage for rural communities. In the study period 2003-2015, about 9% of the cork oak woodlands of the study areas have been affected by wildland fires. Though this represents a relatively small percentage of the total *Quercus suber* L. surface area, cork oaks burned can lead to relevant losses of ecosystem services and income, as well as to the death of monumental and ancient trees, which are key components of cultural landscapes and agro-pastoral areas in Sardinia, Corsica and Catalonia. Wildfires nearby cork oak forests were primary linked to the occurrence of dry summers, and the most of the *Quercus suber* L. area burned was related to a few large fire events associated to extreme weather conditions. It is thus likely that the future changes in climate will further increase wildfire risk for Mediterranean forests, unless significant efforts are made to promote appropriate forest management and planning strategies. Socio-economic changes can even foster the occurrence of high-intensity wildland fires, due to the magnitude of land use changes and the abandonment of forest and rural activities.

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Figure 1

Click here to access/download;Figure;Figure 1_Study areas, QS distribution, and fires_5.jpg

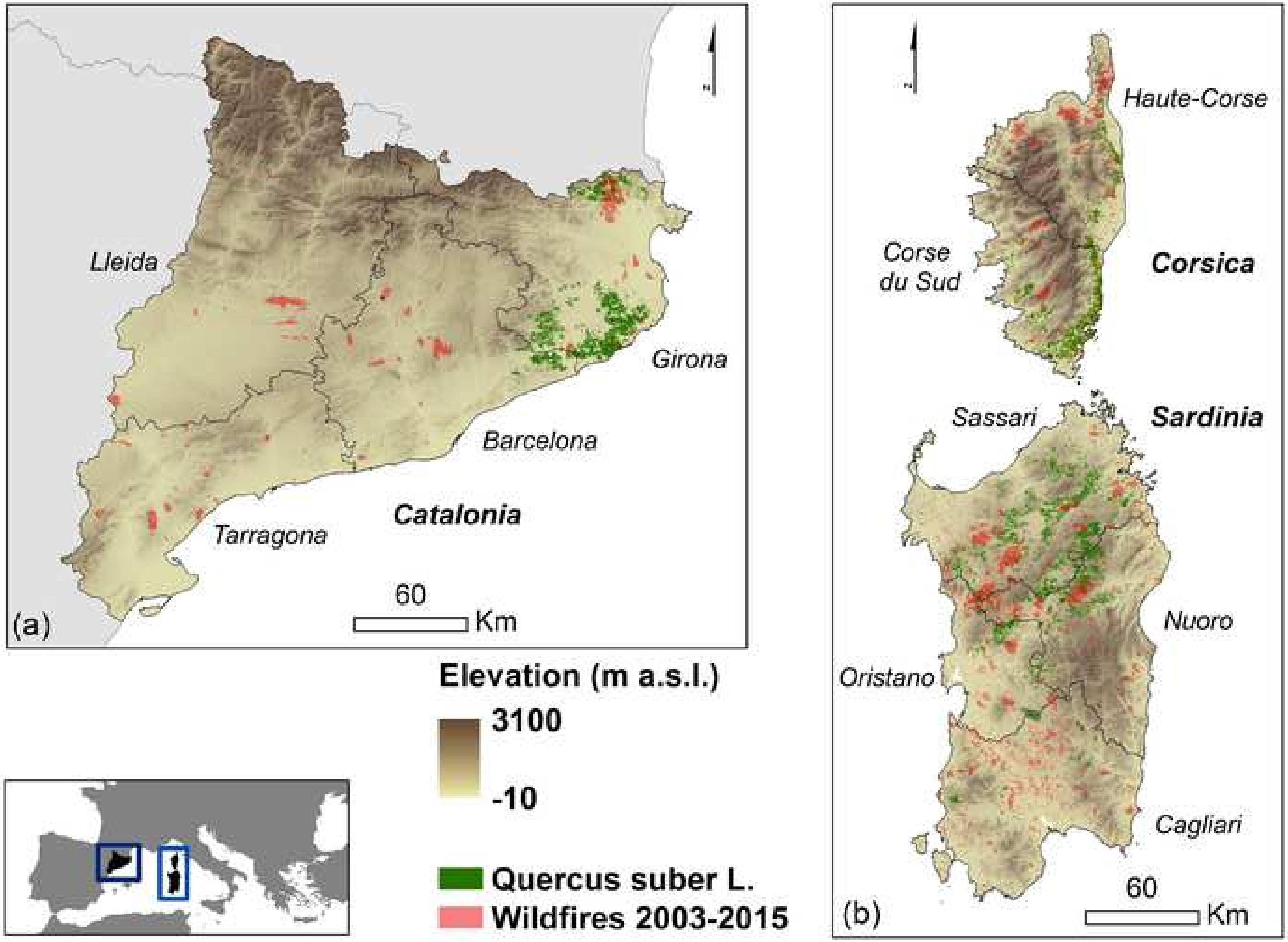

Figure 2 

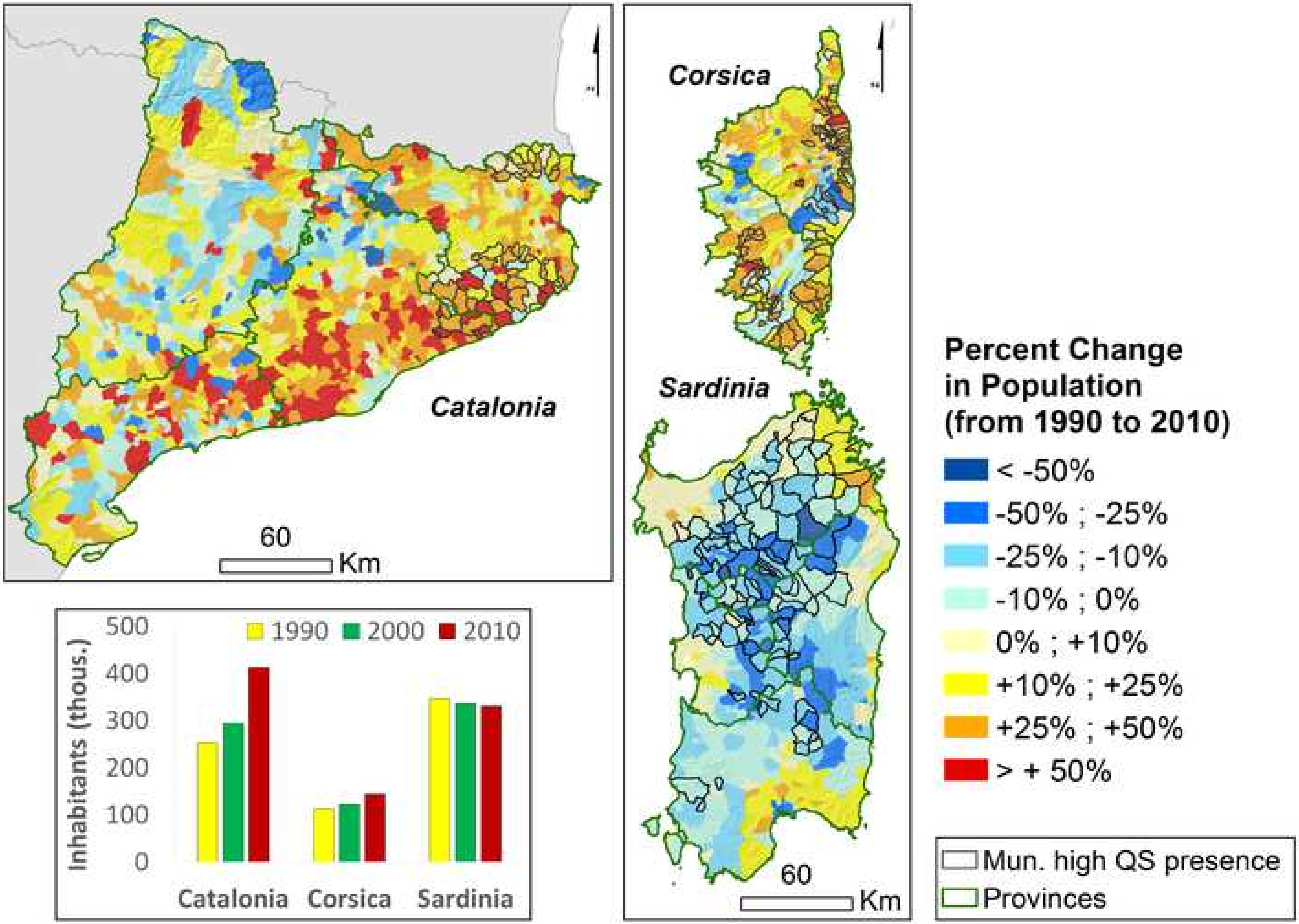
Catalonia
60
Km
Corsica
Sardinia
60
Km
Percent Change in Population (from 1990 to 2010)
< -50%
-50% ; -25%
-25% ; -10%
-10% ; 0%
0% ; +10%
+10% ; +25%
+25% ; +50%
> + 50%
Mun. high QS presence
Provinces
Inhabitants (thous.)
500
400
300
200
100
0
1990
2000
2010
Catalonia
Corsica
Sardinia

Figure 3

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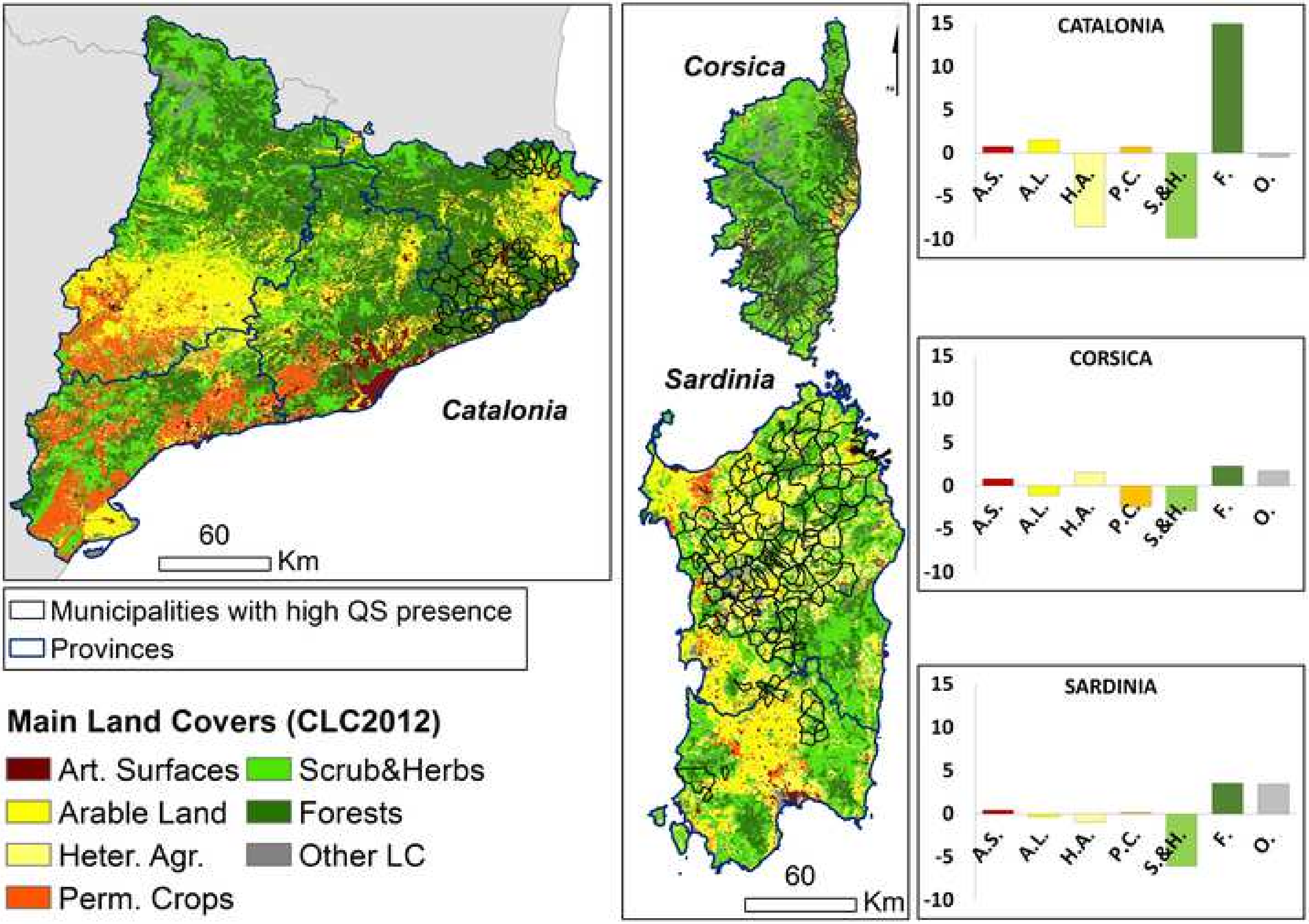
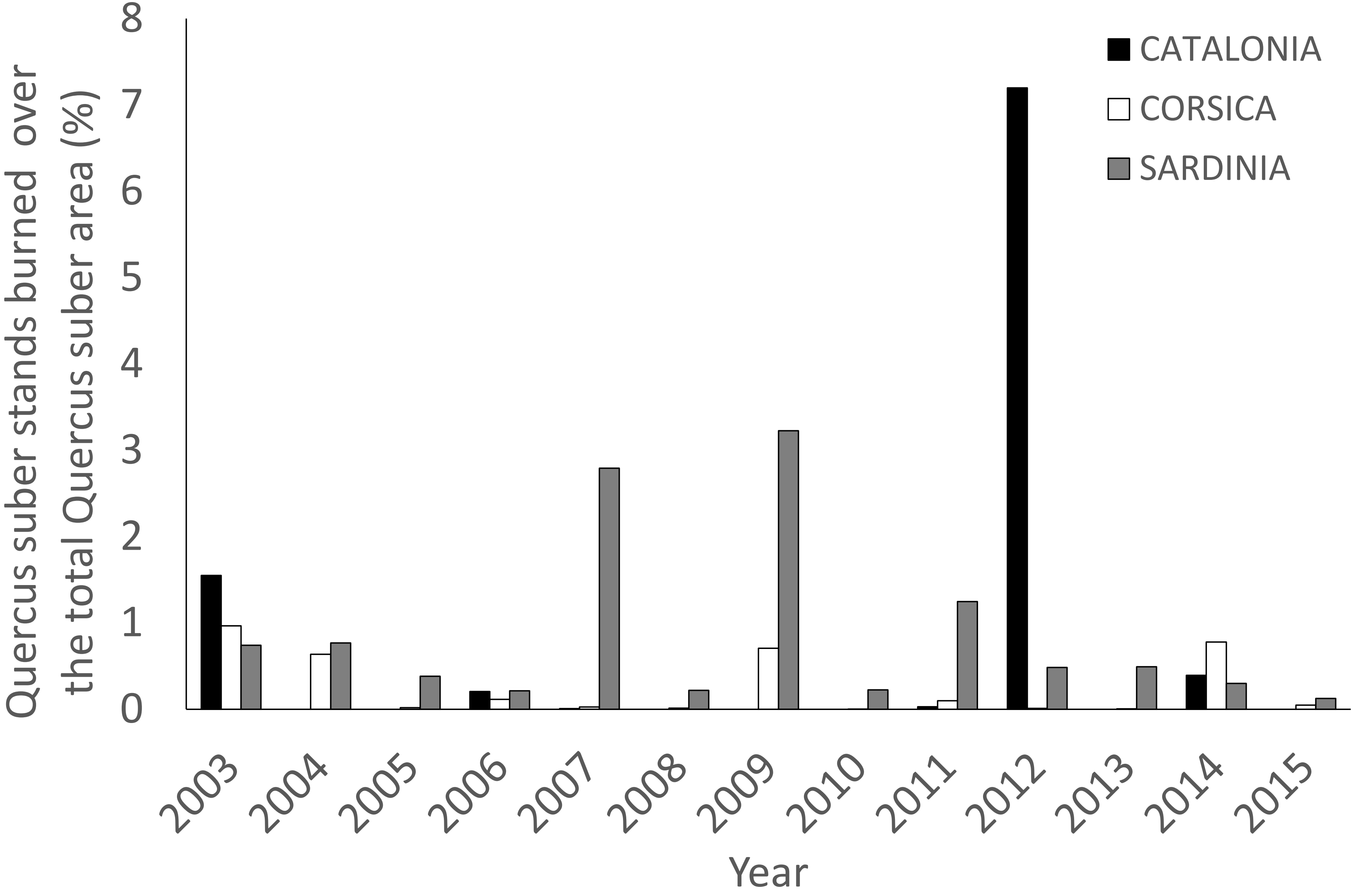
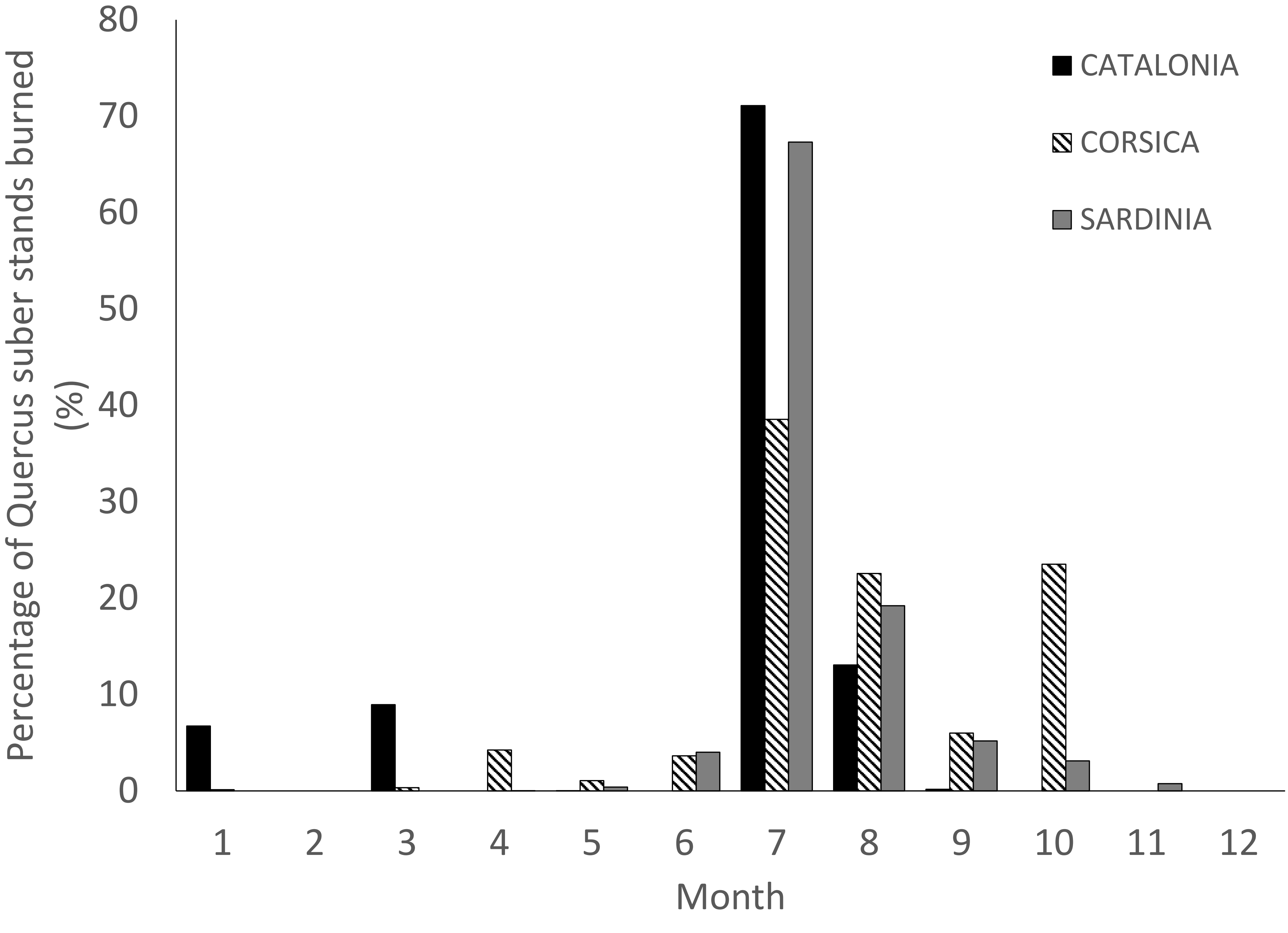


Figure 4



Quercus suber stands burned over the total Quercus suber area (%)
8
7
6
5
4
3
2
1
0
CATALONIA
CORSICA
SARDINIA
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
Year

Figure 5



80
70
60
50
40
30
20
10
0
Percentage of Quercus suber stands burned (%)
CATALONIA
CORSICA
SARDINIA
1
2
3
4
5
6
7
8
9
10
11
12
Month

Figure 6a

Click here to access/download;Figure;Figure 6a_1990-2002_ter.jpg

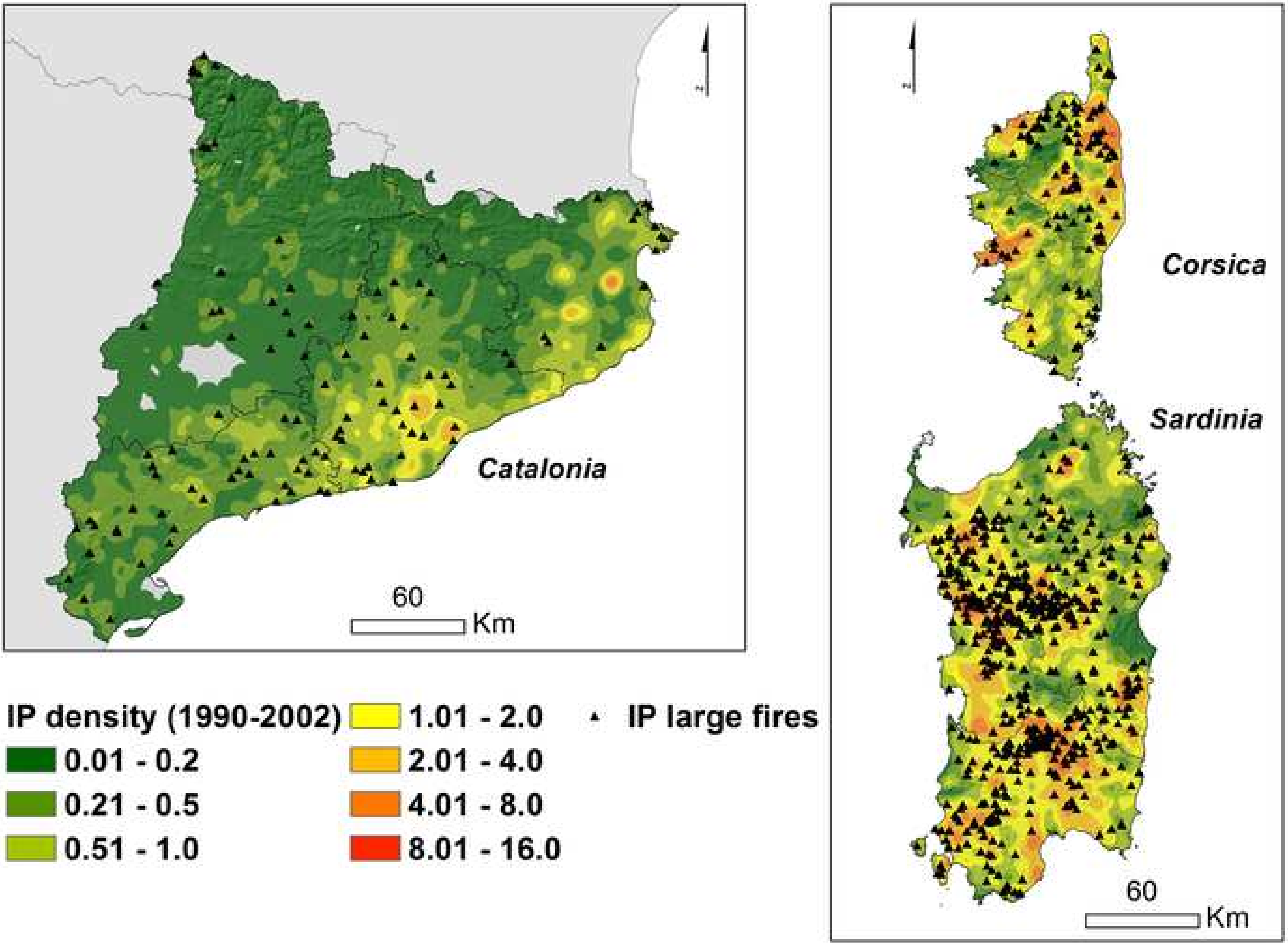
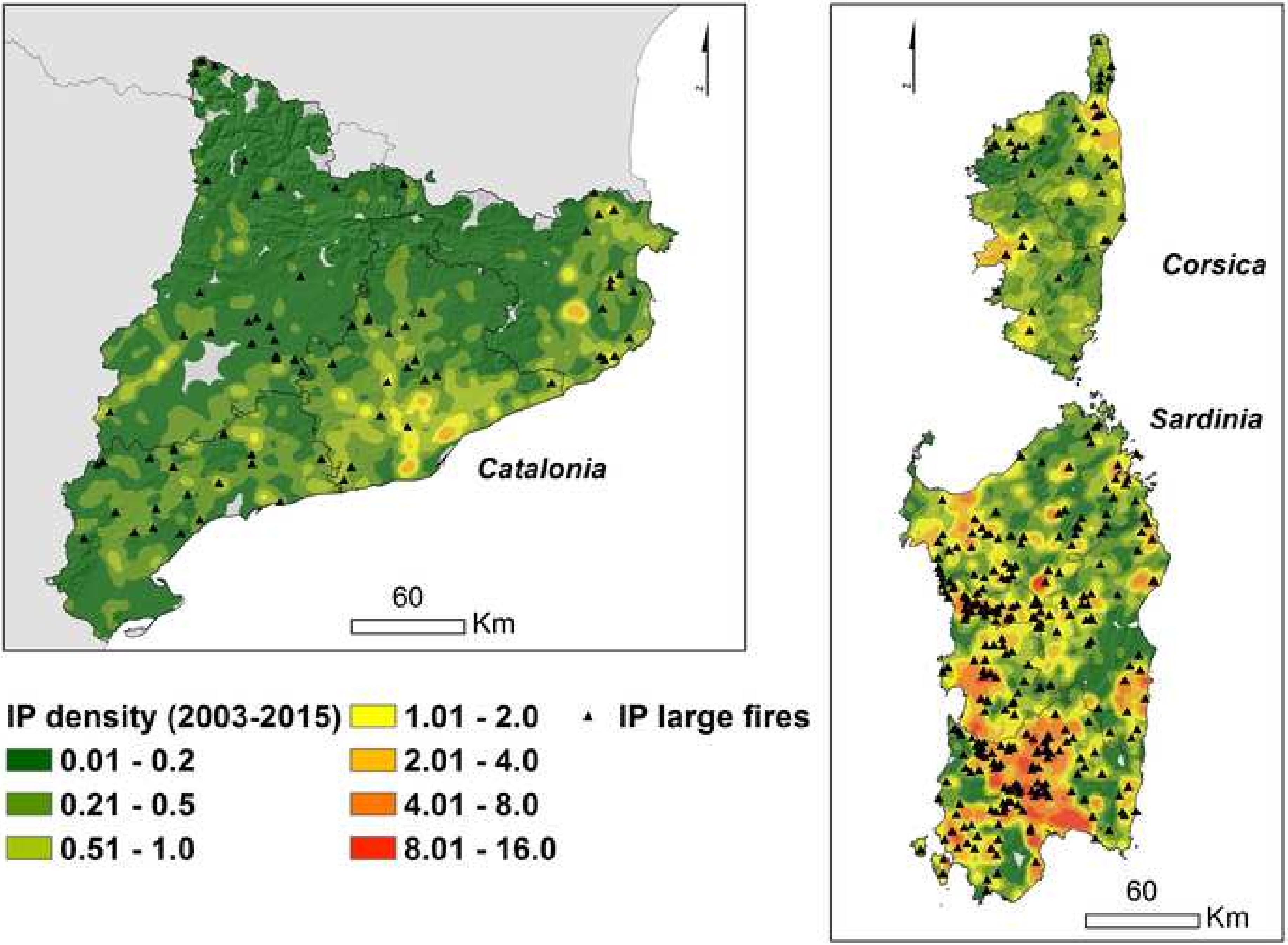
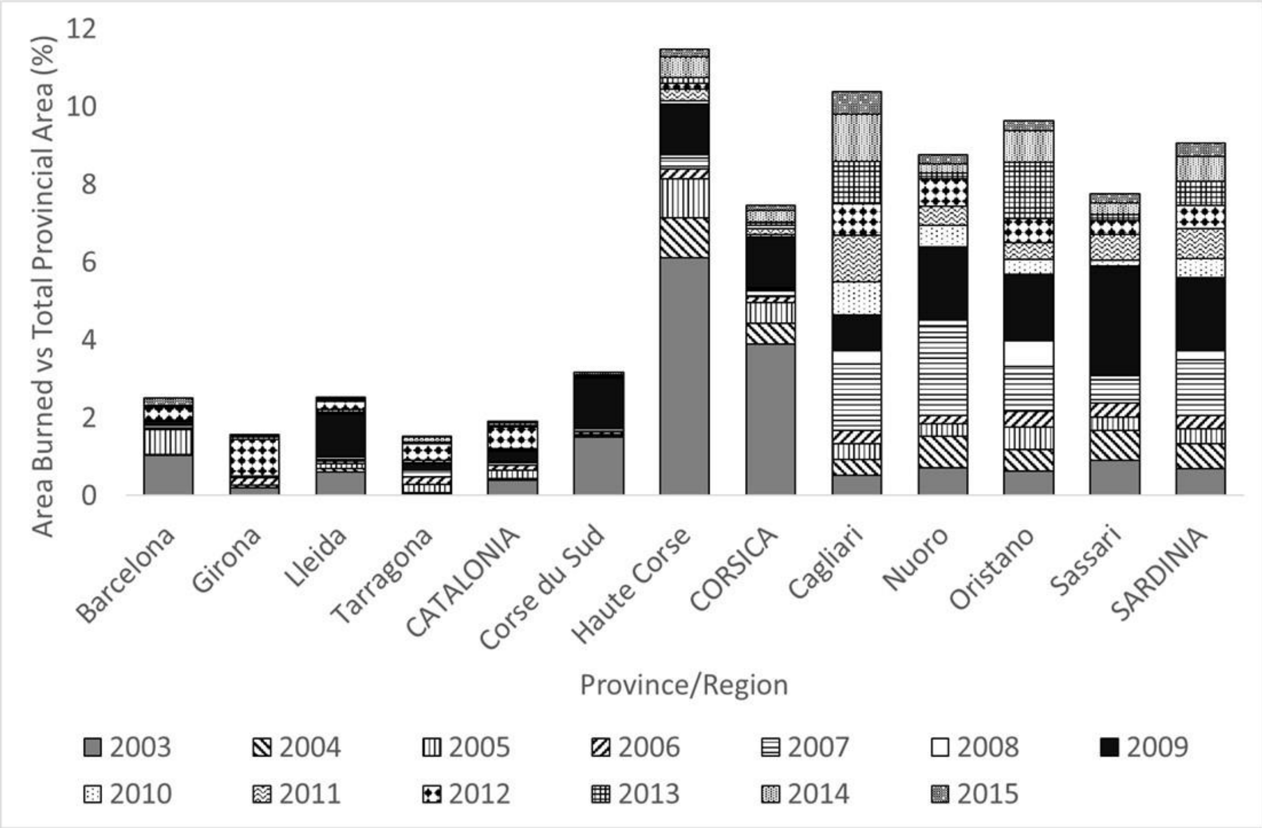


Figure 6b

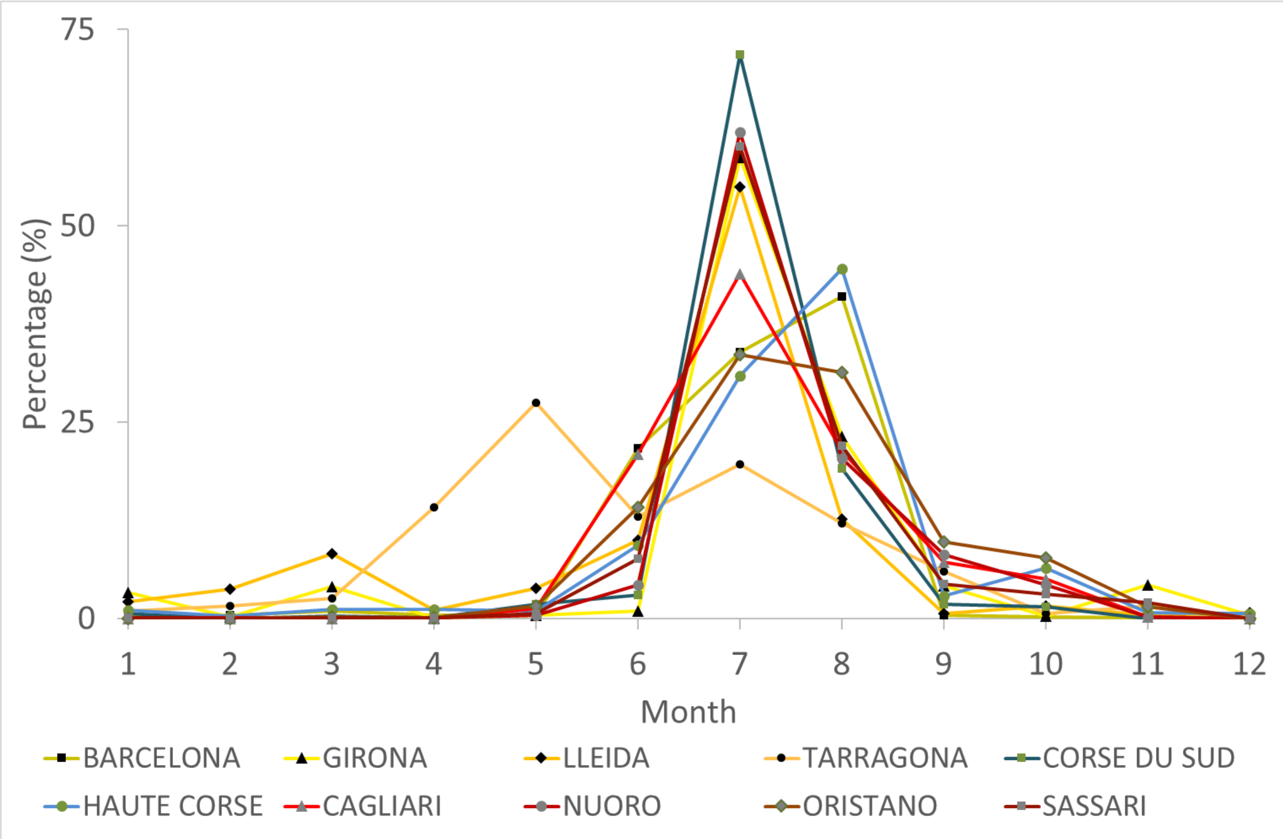




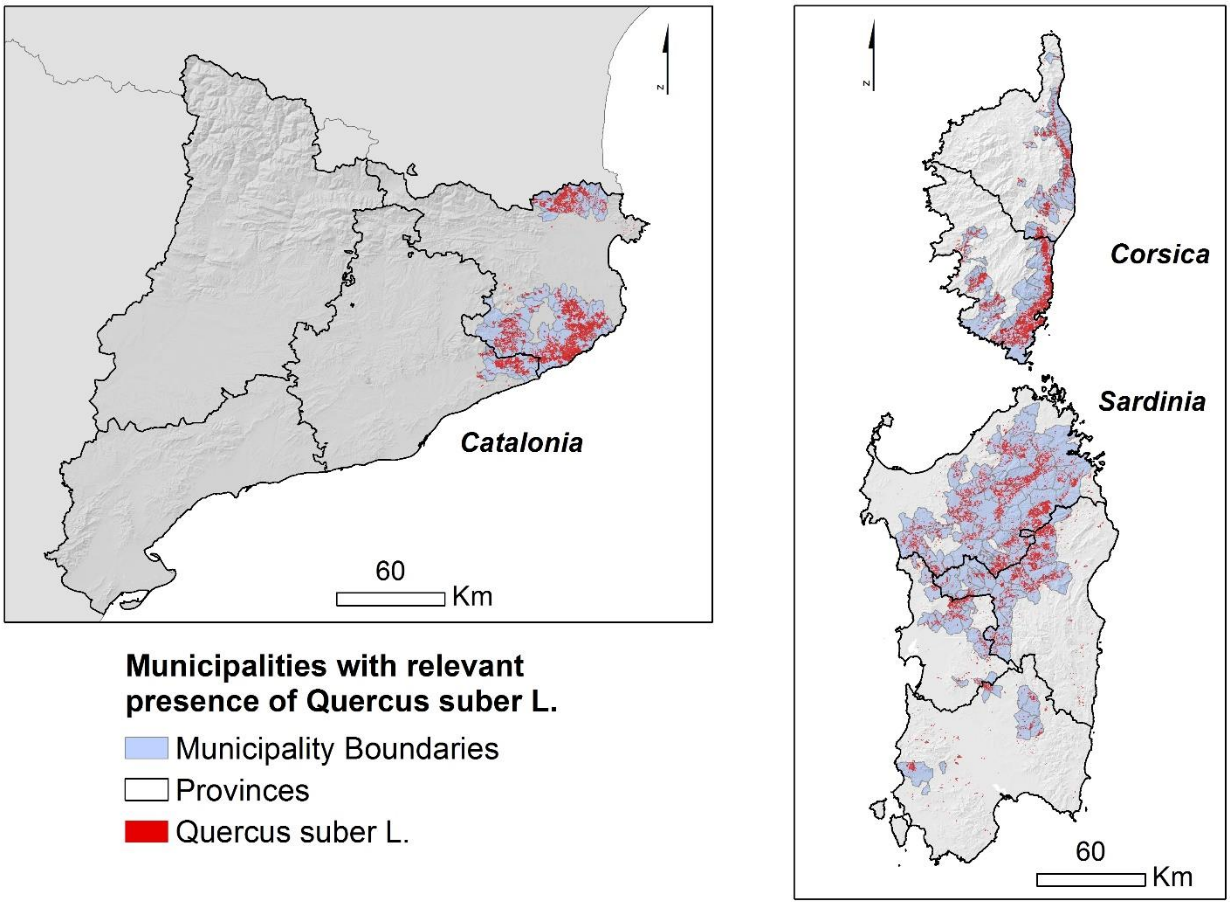
Catalonia
60
Km
Corsica
Sardinia
60
Km
IP density (2003-2015)
0.01 - 0.2
0.21 - 0.5
0.51 - 1.0
1.01 - 2.0
2.01 - 4.0
4.01 - 8.0
8.01 - 16.0
IP large fires



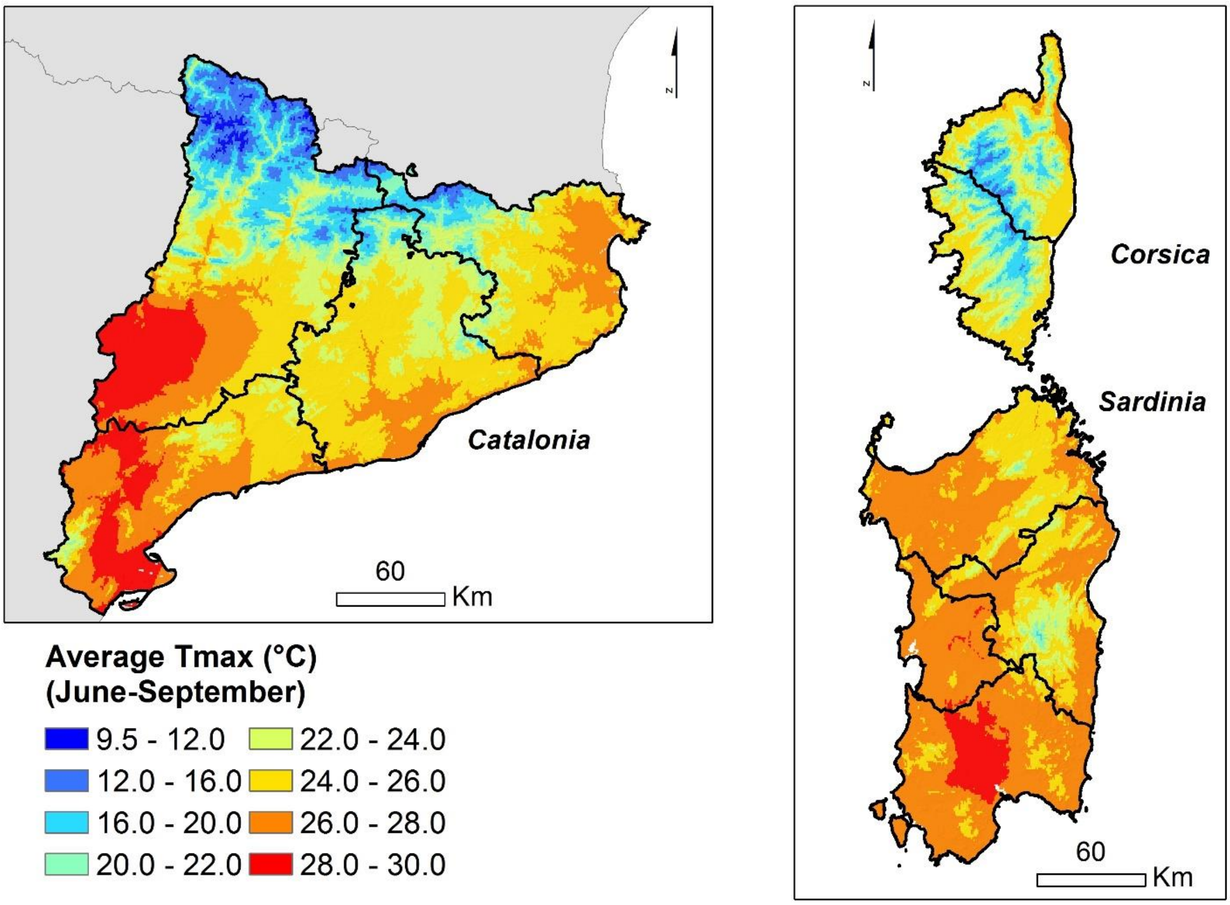

*Supplementary Fig. 1 - Percentage of the annual provincial and regional areas affected by wildland fires in the period 2003-2015.*



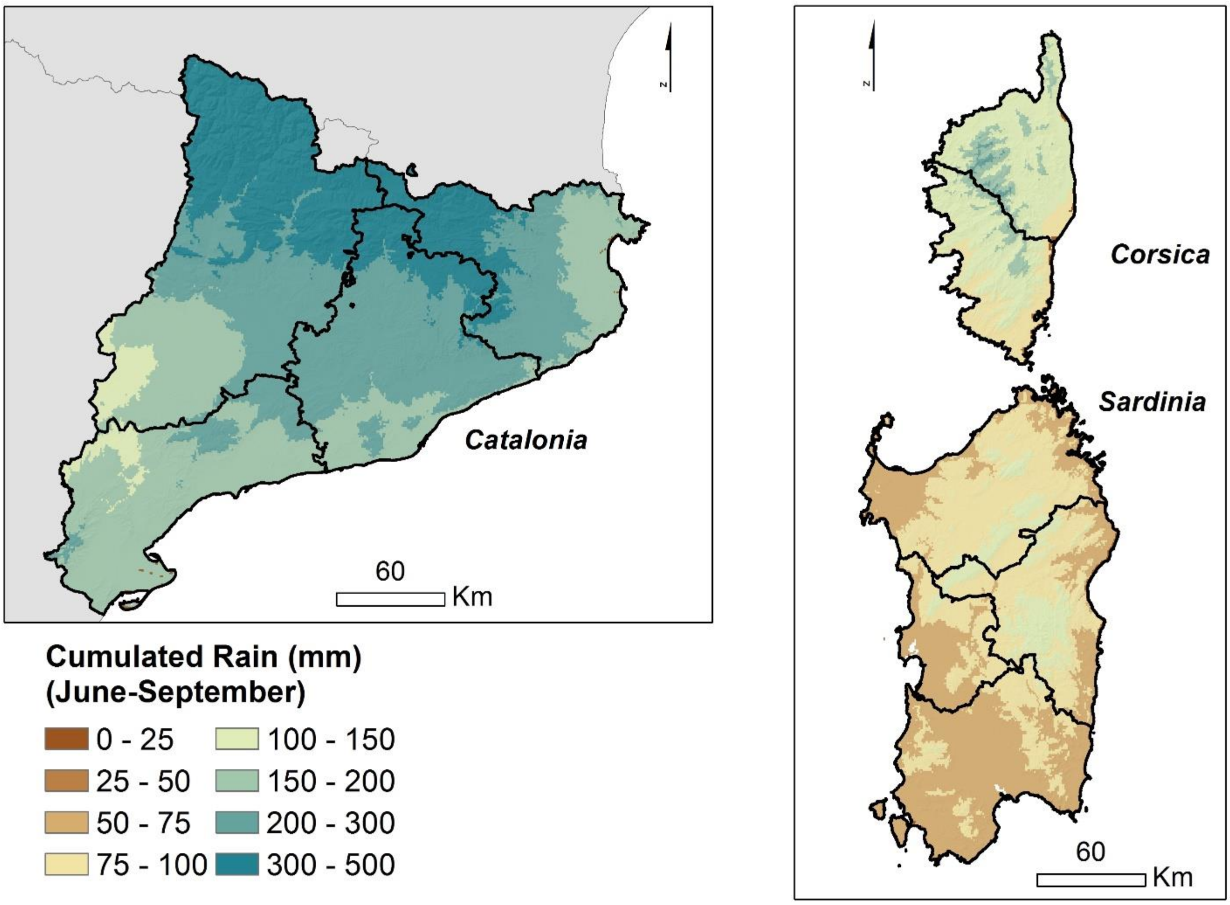

*Supplementary Fig. 2 – Percent total area burned per month at the provincial level for the study areas. The wildland fire data refer to the period 2003-2015.*



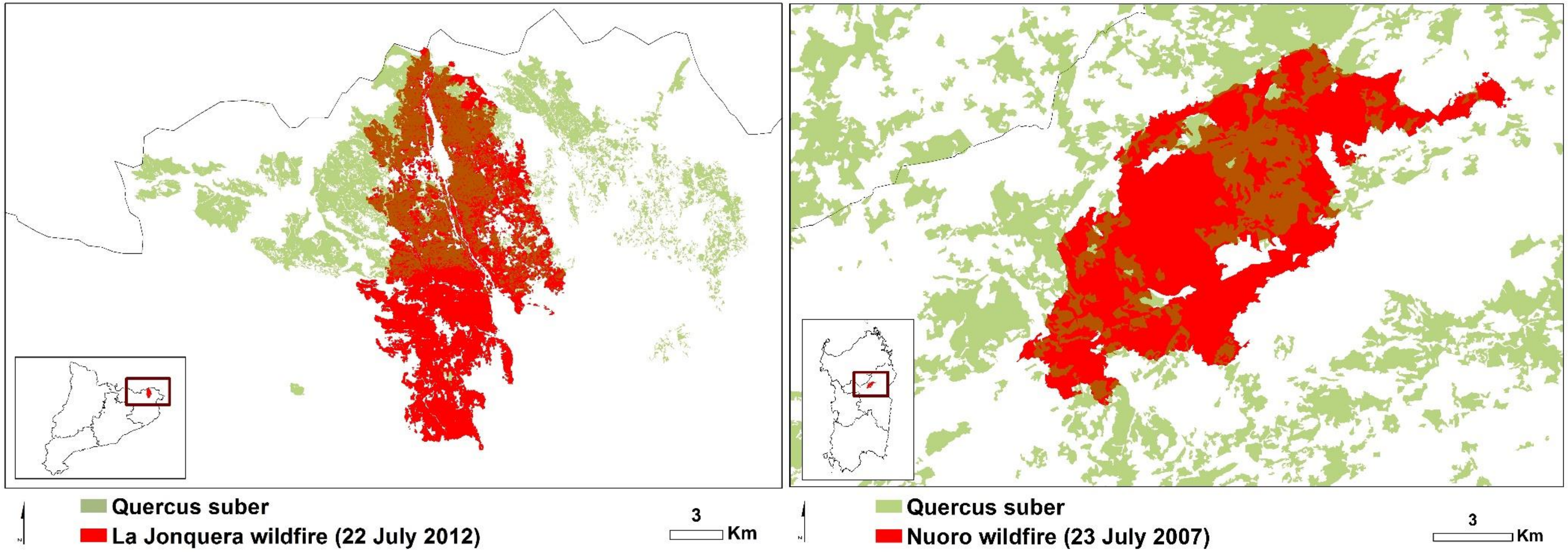

*Supplementary Fig. 3 - Map of the municipalities characterized by a presence of Quercus suber L. woodlands above 5% of the municipality area*




*Supplementary Fig. 4 - Map of the average maximum temperatures of the months June-September for the study areas. Climate data from the 1-km resolution "WorldClim version 2" (Fick and Hijmans 2017)*




*Supplementary Fig. 5 - Map of the average cumulated precipitation of the months June-September for the study areas. Climate data from the 1-km resolution "WorldClim version 2" (Fick and Hijmans 2017)*

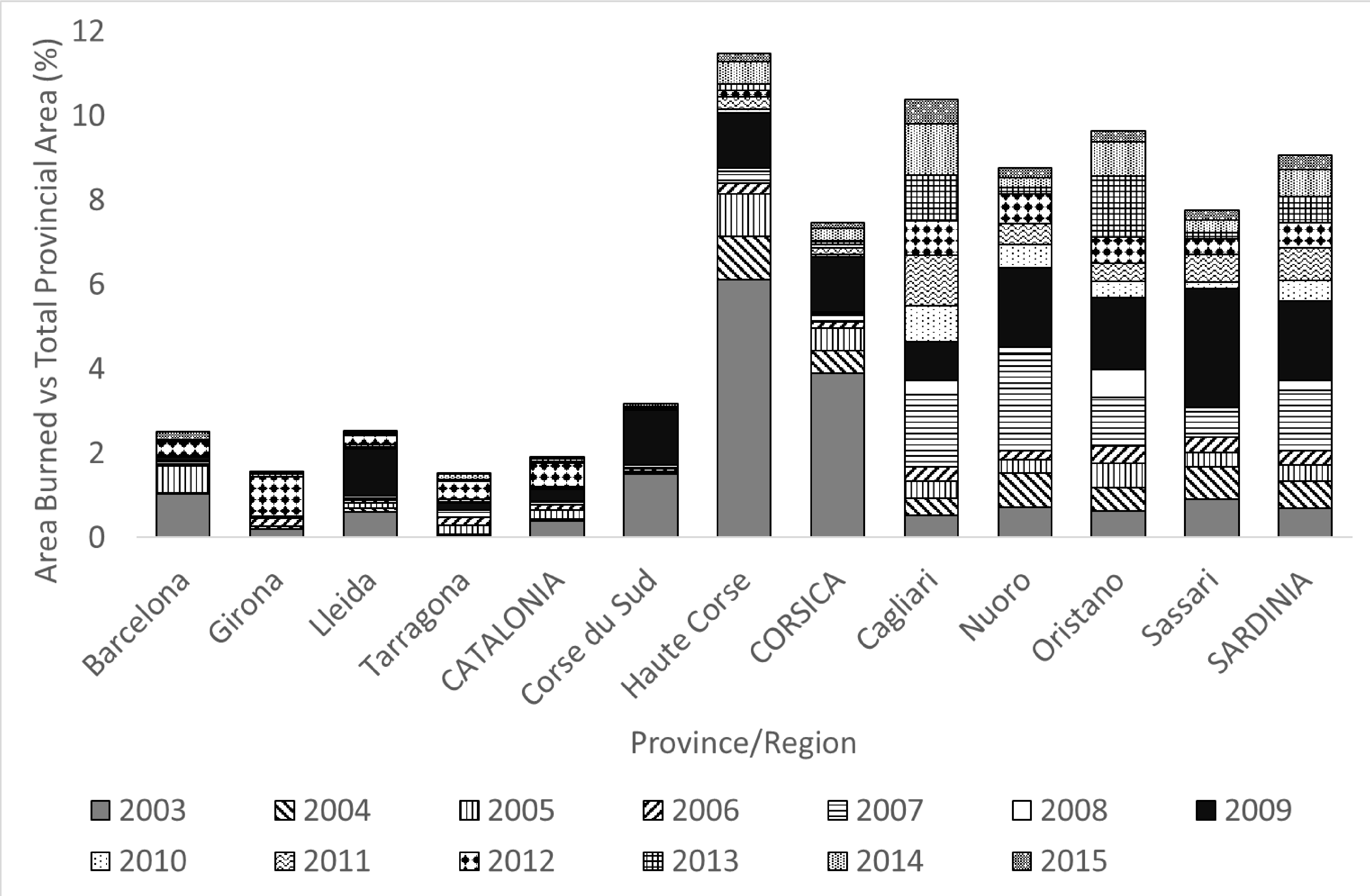



*Supplementary Fig. 6 – The role played by large wildland fire events on Quercus suber L. woodlands area burned. Red areas indicate the fire perimeters of La Jonquera (about 10,500 ha, on the left), which affected the province of Girona on July 2012, and Nuoro (about 9,000 ha, on the right), which affected the province of Nuoro on July 2007. As showed in the manuscript, large wildland fires substantially contributed to the total cork oak area burned in the study areas.*

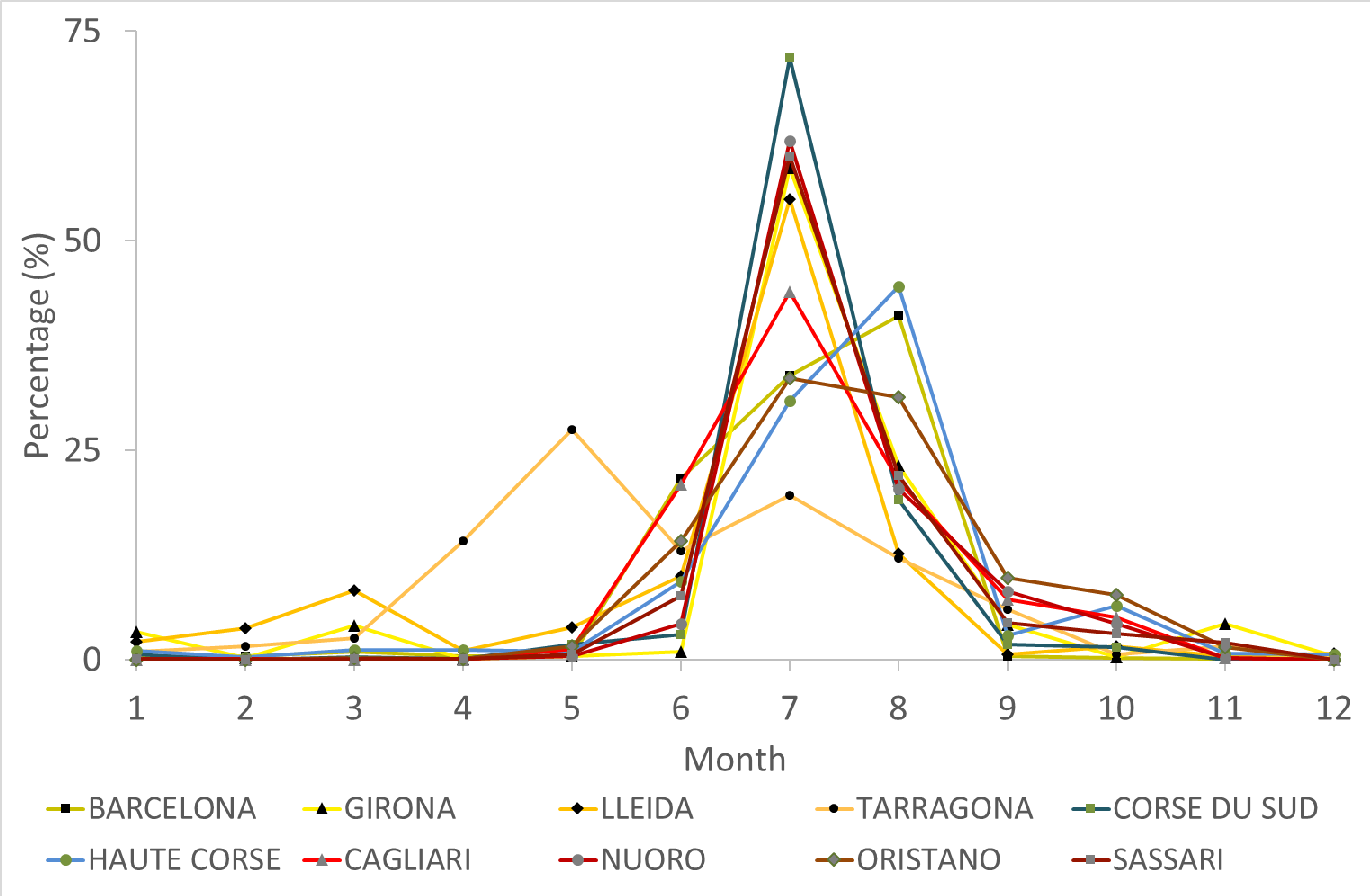
***Table 1***. *Percentage of fire ignition locations as a function of the distance from cork oak woodlands and provinces for the study period 2003-2015 and for the previous 13-years in the study areas.*

| | ***2003-2015*** | | | ***1990-2002*** | | |
|---|---|---|---|---|---|---|
| **Province (Region) / Distance** | **0-1 km** | **1-10 km** | **>10 km** | **0-1 km** | **1-10 km** | **>10 km** |
| Cagliari (Sardinia) | 13.45 | 79.16 | 7.39 | 18.46 | 75.45 | 6.10 |
| Nuoro (Sardinia) | 42.68 | 56.64 | 0.68 | 43.99 | 52.73 | 3.29 |
| Oristano (Sardinia) | 23.68 | 75.77 | 0.54 | 35.33 | 64.05 | 0.62 |
| Sassari (Sardinia) | 50.51 | 46.17 | 3.32 | 56.10 | 41.74 | 2.16 |
| Corse du Sud (Corsica) | 31.60 | 52.53 | 15.87 | 31.66 | 52.45 | 15.89 |
| Haute-Corse (Corsica) | 33.71 | 53.05 | 13.23 | 35.42 | 52.87 | 11.72 |
| Barcelona (Catalonia) | 2.67 | 20.65 | 76.68 | 3.41 | 18.86 | 77.73 |
| Girona (Catalonia) | 43.51 | 37.08 | 19.42 | 39.87 | 34.73 | 25.39 |

Suppl. Figure 1

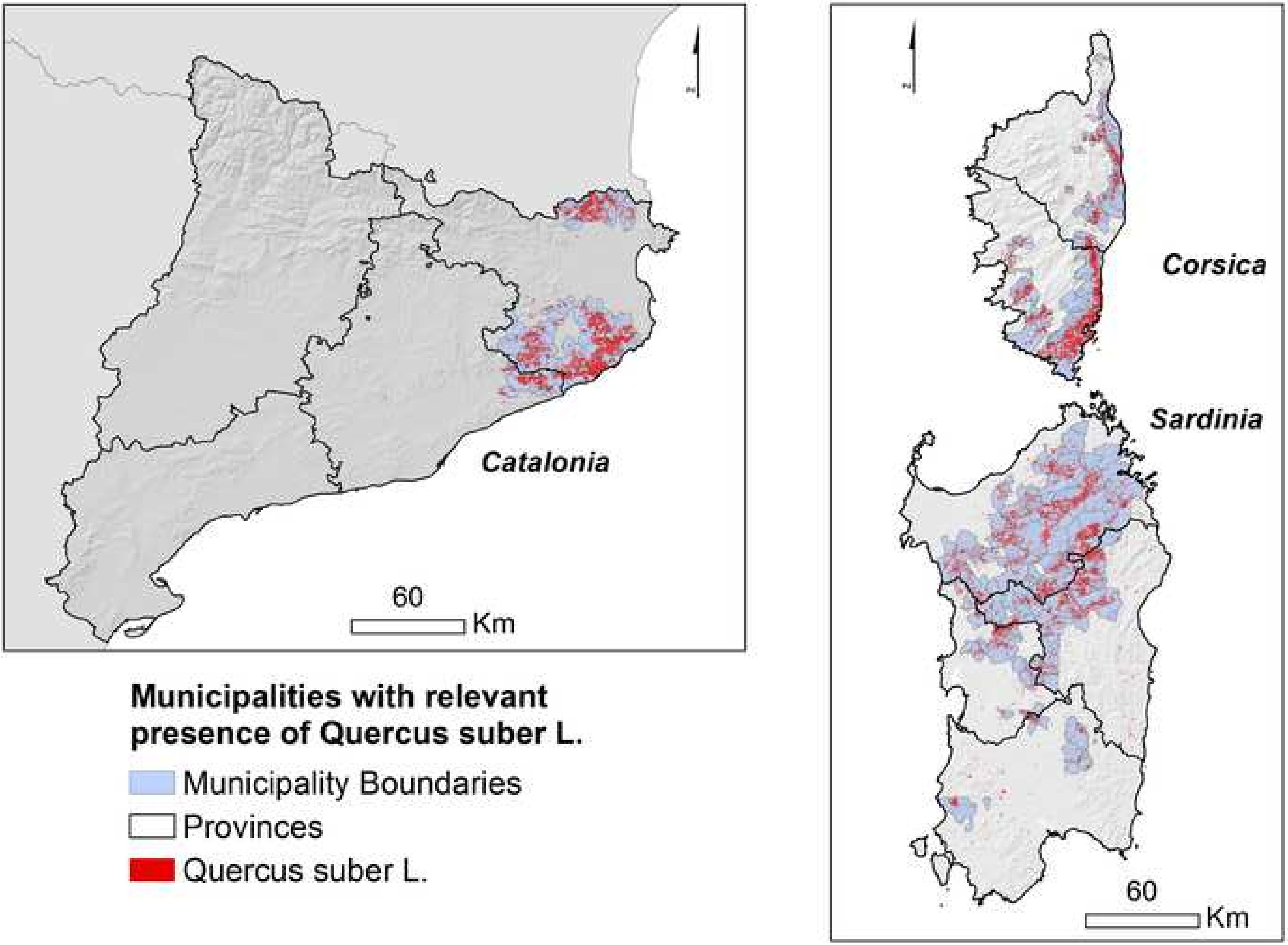


Suppl. Figure 2



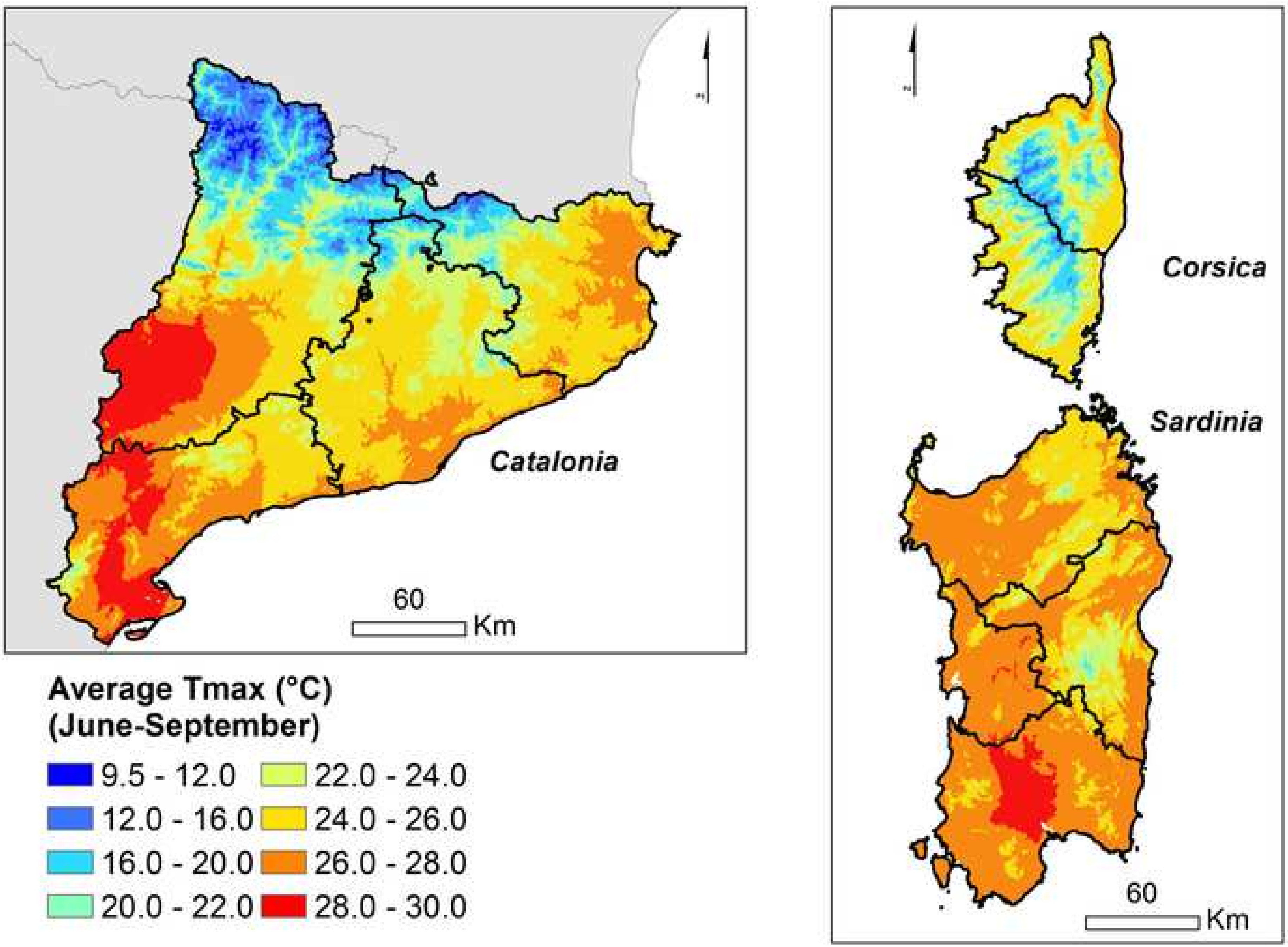
Suppl. Figure 3





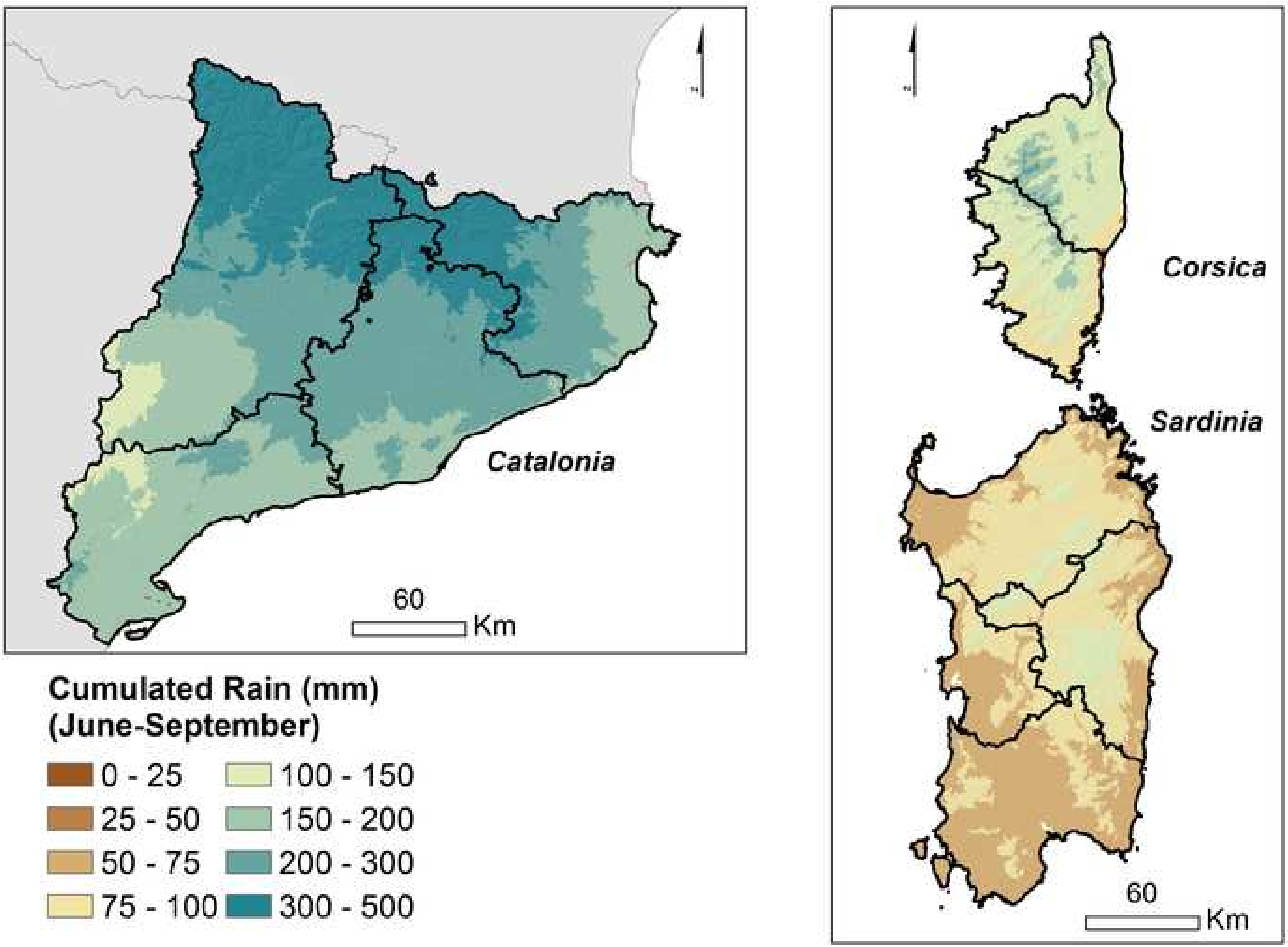
Suppl. Figure 4





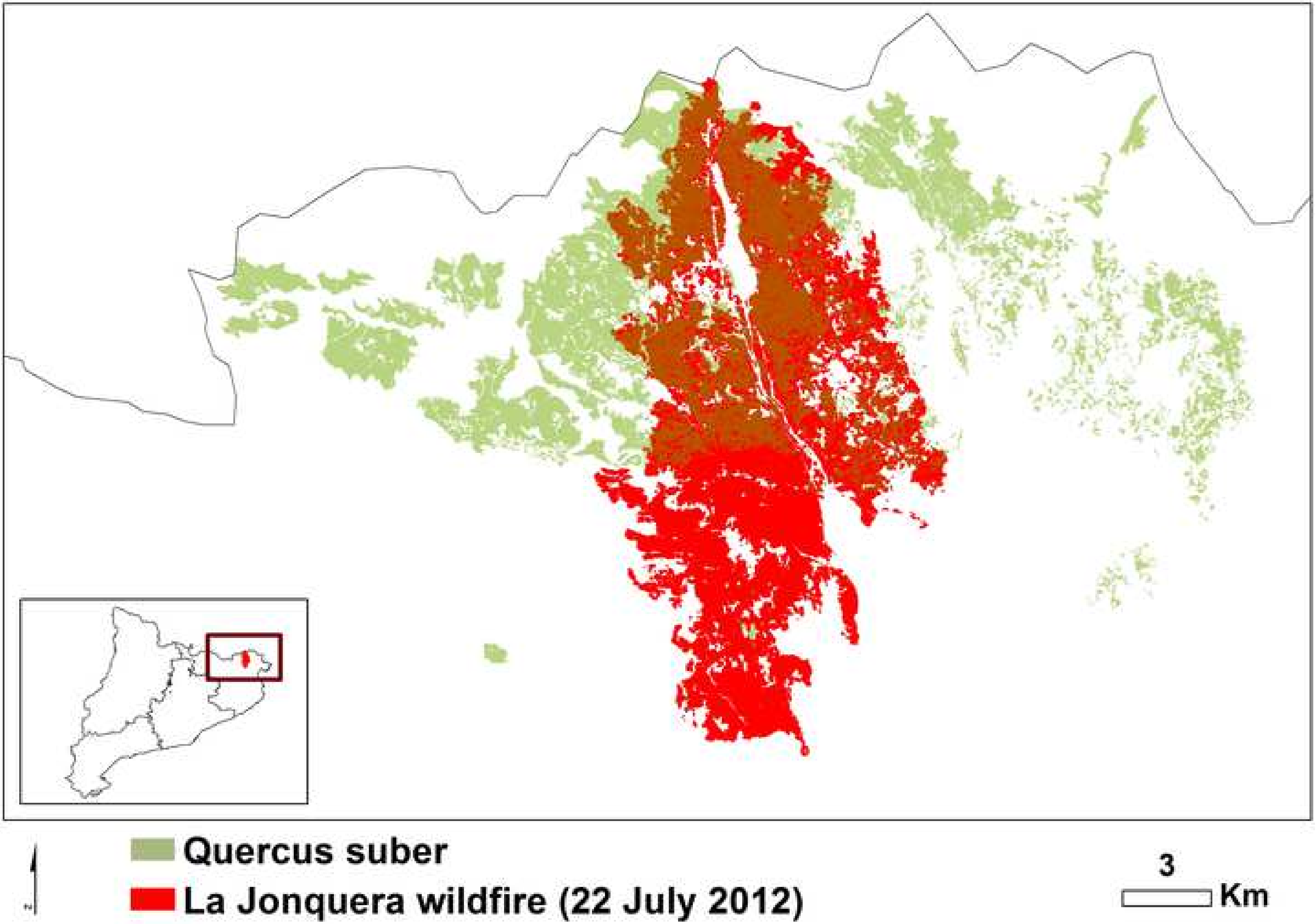
Suppl. Figure 5





Suppl. Figure 6a





Suppl. Figure 6b