Disentangling the probability of large fire occurrence in Mediterranean forests: Management guidelines from a multiscale approach.

Journal: International Journal of Wildland Fire

Date: September 2014

Laura Lasheras Álvarez

Director: Lluís Brotons

(Centro Tecnológico Forestal de Catalunya)

Codirector: Assu Gil Tena & Andrea Duane

Master: Ecología Terrestre y gestión de la Biodiversidad, Especialidad de Ecología Terrestre

Additional information

This master project was started in February of 2014. The first phase was related to data management and preparation, continued by data analysis and finished with project writing. Further details about my contribution are explained bellow.

Data management: Some calculations within databases of the National Forest Inventories were needed. Besides, I separated brunt from unburnt plots and slightly different calculations were done within each group; some information was only taken into account for burnt plots.

Data preparation: I performed kriging and Thiessen interpolation techniques for different forest structure variables and prepared vegetation distribution maps. I also computed the percentage of each land cover around each ignition and control point and the mean value of forest structure variables within forested areas in the selected surrounding areas.

Analysis: I built three final Binary Logistic Regression Models in order to understand the relation between forest structure variables, land covers presence and fire occurrence. I used these models to build a fire risk map for each period considered and another about the increase-decrease of fire risk in Catalonia between the two periods considered.

Writing and project final preparation: I am the principal author of the project although draft corrections were made by Assu Gil, Andrea Duane and Lluís Brotons.

Abstract

Fire is one of the main disturbances in Mediterranenan ecosystems. In the recent decades, in Catalonia (NE Spain), the number of fires has decreased while burnt area has increased. This is related to changes in land use, climate and fire suppression policies which influenced horizontal and vertical fuel continuity. From all the factors influencing fire risk only fuel load is manageable by humans. For this reason it is important to understand the role of different land covers and forest structure in fire occurrence. This study aimed to understand the determinants of large fire occurrence at two different scales, 500m and 2000m around the ignition point (local and landscape scale, respectively). A binary logistic regression model was built using ignition points from the period 1989-2012 and considering 1000 control points. Forest structure variables obtained through interpolation techniques throughout Catalonia and land cover types were established as the independent variables at the two considered scales. A risk map for large fire occurrence in Catalonia was also built.

Mediterranean pine forests and shrublands were the main variables influencing positively large fire occurrence. Specifically, Mediterranean pine forests with intermediate values of basal area and high understory increased the risk of large fires. Although large fires do not usually start in mixed forests, these forests were important at the scale at the landscape scale (2000m) probably because of their vertical continuity. Results showed that a multiscale management would be necessary which should focus on the landscape mosaic of different land cover types and less fire prone forest structures, particularly considering the uncertainty associated with global change and the large fires' risk increase throughout Catalonia.

Keywords: Basal area, Catalonia, Fire regime, Mixed forest, Pine, Shrublands, Spain, Understory.

Introduction

Fire is one of the main disturbances in many terrestrial ecosystems having a key role in their distribution and composition (Thonicke *et al.* 2001; Bond *et al.* 2005). In fact, it is impossible to understand the distribution of some biomes and plants without considering fire (Bond and Keeley 2005). Fire importance in Mediterranean ecosystems is due to their climatic characteristics which make fuel load prone to fire (dry and warm summers with mild winters) (Lloret 1996). There are three key factors indispensable for fire occurrence: oxygen, heat and fuel (Pyne *et al.* 1996). When fire occurs, its behavior is controlled by topography, fuel load and meteorology (Rothermel 1983). Finally, fire regime, which describes the pattern and frequency of wildfires, is determined by: 1) ignition source, 2) fuel structure, 3) primary productivity and 4) seasonality (Pausas and Keeley 2009).

In the recent decades, instead of the high-frequency, low-severity surface fire regime which is characteristic from Mediterranean areas, more high-intensity, crown fires are occurring (Pausas and Fernández-Muñoz 2011). Humans play an important role in fire regime in different ways:

a) Widespread land-cover change due to large-scale socioeconomic changes (Pausas and Fernández-Muñoz 2011). Rural land abandonment in the last decades of the 20th century has lead to changes in traditional agriculture and cattle raising involving forest expansion and an increase of fuel accumulation (Giralt 1990; Debussche *et al.* 1999). This change affects directly to the parameter of fuel load increasing its availability and vertical and horizontal continuity.
b) Human fire ignition increase. There has been a rise of human ignitions related to a larger area of urban-wildland interface during last decades (Terradas *et al.* 1998; Pausas 2004).
c) Fire suppression techniques (Brotons *et al.* 2013), public awareness and changes in policies (Cui and Perera 2008; Krawchuk *et al.* 2009). Fire suppression policies are effective in reducing the total number of fires, but large fires still have an important contribution to the total burned area (Miller and Urban 2000; Díaz-Delgado *et al.* 2004).
d) Changes in climate related to the increasing dryer and warmer conditions in the last decades have been related to an increase of fire risk (Piñol *et al.* 1998).

Due to these changes, it is important to understand how to minimize fire risk occurrence. From the factors providing fire occurrence, the only factor controllable by humans is land cover composition and forest structure (Duane *et al.* Submitted). Forest managers usually use information on stand density, species composition, fuel availability at surface level and vertical structure of the stands to evaluate fire risk. Fire risk models only based on climatic variables should not be used for management purposes because climate is not controllable by humans (Finney 2005; Gonzalez *et al.* 2006). To limit wildfire occurrence and size, fuel treatments such as cleaning and thinning are usually prescribed as they can alter fire behavior and its spreading extent (Finney 2001; Hirsch *et al.* 2001; Gonzalez *et al.* 2005). These fuel treatments usually affect horizontal and vertical continuity (Torras and Saura 2008). In addition, these management practices are usually focused on the vulnerability of the forests at a stand scale, but no assessment of the forest landscape scale vulnerability in a mid-term period has been done to date. More scientific evidences of forest structures prone to burn at the landscape scale are needed aiming to help landscape and forest management actions at regional scales (Pausas and Paula 2012). National policies at a mid-long term need to be accompanied from more insights into landscape vulnerability situation and fire management actions.

How fire spreads and in which direction is determined by different proneness within land cover types and forest structure, among other factors. Land cover selectivity is very high while a fire is still small, but it tends to decrease when a fire becomes larger (Barros and Pereira 2014). Thus, the scale at which landscape fire vulnerability is assessed can be determinant in fire diagnostic situation. It is important to consider the role of the different land cover types at different scales when assessing their effects on fire occurrence probability.

Given the fact that the spatial distribution of land cover patches and forest structure influences fire occurrence and behavior (Miller and Urban 2000), and in the situation of facing the unknown consequences of global change, the main objective of this study was to build a predictive model of large fire occurrence whereas testing alternative hypothesis of the factors affecting fires such as forest composition and structure, or spatial scale of fuel arrangement. Specifically, the following points have been addressed: a) to assess how forest structure influences the occurrence of large fires; b) to determine differences among taking into account local or landscape scale in large fire prediction; c) to disentangle which land cover types and forest structure variables at each scale improve large fire prediction. This model was also used to build a fire occurrence risk map for Catalonia. This map showed the risk of occurring fires greater than 50 ha in a certain point (large fires in this study). The related hypotheses of the study were: 1) the local scale will have a greater influence on fire occurrence than landscape scale due to the key role of land cover and forest structure features near the ignition point; 2) shrubs and forest land cover types will have a positive influence in fire occurrence regarding other burnable land cover types (e.g. crops and herbaceous covers) because of fuel load availability; and 3) forest structure features boosting vertical and horizontal continuity will increase fire risk occurrence. Changes in fire risk were also evaluated between 2000 and 1989 (forest inventory data availability), contrasting the hypothesis of an increase in large fire risk in the recent decades.

Material and methods

Study area

The study was carried out in Catalonia (northeast Spain) (Figure 1). The climate is predominantly Mediterranean, with dry summers and humid winters. There are big differences in precipitation and temperature within the region mainly determined by topography. Elevation ranges from sea level to 3103 m.a.s.l. in the Pyrenees (northern part of Catalonia). Precipitation fluctuates from 1200mm at some Pyrenean regions to 400mm at the central Ebro depression while temperature also varies from averages of 17°C in the south to averages of 0°C in the northern high elevation part (Ninyerola *et al.* 2000)

Figure 1 approximately here.

Catalonia occupies an area of 32115 km^2 and approximately 60% of the region is covered by forests, 38% from which correspond to woodlands and 22% to shrublands (Burriel *et al.* 2001) (Figure 1). About of 90% of the total number of tree species in Catalonia are within the following 14 most common tree species: *Pinus halepensis* Mill. (ca. 20%)*, Pinus sylvestris* L. (ca. 18%)*, Quercus ilex* L. (ca. 15%)*, Pinus nigra* Arnold. (ca. 11%)*,* and *Pinus pinea* L.*, Pinus uncinata* Mill.*, Pinus pinaster* Ait.*, Quercus suber* L.*, Quercus humilis* Mill., *Quercus petraea* Matts. Liebl.*, Quercus faginea* Lam.*, Fagus sylvatica* L., *Abies alba* Mill. and *Castanea sativa* Mill. Mixed forests represent about of 40% of the Catalan forests (Piqué, Vericat, *et al.* 2011).

During the studied period (1989-2012), more than 200000 ha were affected by fires greater than 50 ha. Although the number of fires in the last decades has decreased, the amount of burnt area has increased (Díaz-Delgado *et al.* 2004). Larger fires in Catalonia are usually associated with coniferous forests and shrublands while grasslands and broadleaved forests are more usually affected by smaller fires (Díaz-Delgado *et al.* 2004).

Fire data

Fire data were provided by the regional government and by the firefighters from 1989-2012. Only fires larger than 50 ha were considered, since the information on smaller fires is not always available. In total, 234 ignition points were available for this period. Specifically, 136 ignitions occurred during 1989-1999 and 98 during 2000-2012. From the initial ignition point dataset, only 221 were used because the accuracy of the data from 13 ignition points in *La Vall d'Aran* is doubtful (Servei de Prevenció d'Incendis, personal communication). Ignition points were divided in two periods according to the Second and Third Spanish National Inventory dates (see next subsection).

Forest structure data characterization

Three vegetation types were chosen in this study to characterize forest structure because of their dominance in Catalonia and occupation in the most fire prone parts of the region. The chosen vegetation types were: monospecific forests of *Pinus sp.* including *Pinus halepensis, Pinus nigra* and *Pinus pinea* (Mediterranean pines); monospecific forests of *Quercus sp.* including *Quercus ilex* and *Quercus suber* (Oaks) and mixed forests of *Pinus halepensis* and *Quercus ilex* (Mixed forests). According to Piqué *et al*. (2011), a monospecific forest was considered when one species has a basal area greater than 80% of the total plot basal area. Mixed forests are those which have one species occupying more than 50% of the total basal area. In this case, the secondary species was also taken into account (Terradas and Rodà 2004; Piqué, Vericat, *et al.* 2011). Mixed forest of *Pinus halepensis* and *Quercus ilex* was chosen because of its dominance in the region and to test the hypothesis of the greater vertical continuity of this forest type in relation to fire (Ganteaume *et al.* 2009). For each species or species combination within a vegetation type, two forest structure variables were computed which represent a surrogate of horizontal continuity (basal area) and vertical continuity (understory height averaged by species occupation).

All forest structure variables were obtained from the Second and Third Spanish National Forest Inventory (2NFI and 3NFI henceforth) (Villaescusa and Díaz 1998; Tercer Inventario Forestal Nacional (1997-2007) 2005). In Catalonia, the fieldwork was carried out in 1989-1990 for the 2NFI and 2000-2001 for the 3NFI. As two different inventories were used for two different periods, two different data sets were obtained: the first one for 1989 and the second one for 2000. The sampling density was about one NFI plot every 1 km^2. In these plots, for trees with a diameter at the breast height (i.e. 1.30 m; dbh) of at least 7.5 cm (tally trees), information on species, dbh, height, and distance and azimuth from the plot centre was recorded. The size of the NFI plots varies depending on dbh, ranging from 5m radius for trees with dbh between 7.5cm and 12.4cm to 25 m for trees > 42.5cm. Information on the abundance, mean height and species composition of small trees (dbh<7.5cm) and bushes was also collected.

Forest structure plot data were interpolated in order to obtain forest structure variables covering all the forest area in Catalonia. First, plots involved in a fire during the previous decade of the Inventory (1980-1988 for 2NFI and 1989-1999 for 3NFI) were separated from unburnt plots. This way, it was possible to treat burnt and unburnt plots separately and to avoid bias due to burnt plots. Information of small trees (dbh<7.5cm) was only used for burnt plots as they were only considered relevant for the study in plots taking part in a regeneration process. The interpolation at the 200m resolution was performed through the kriging technique for unburnt plots (*n*=6601 for 2NFI and *n*=6859 for 3NFI) and through Thiessen polygons for burnt plots (*n*=529 for 2NFI and *n*=344 for 3NFI). The kriging technique consists of predicting the value of a function at a given point by computing a weighted average through an adjusted variogram function from the known values. The variogram is used to describe the degree of spatial dependence in a stationary process (Bivand *et al.* 2013). The Thiessen polygons' technique consists of building polygons whose segments are equidistant to the two nearest sites and vertices are equidistant to three or more sites, the whole polygon area gets the same value as the site inside the polygon (Bivand *et al.* 2013). Although kriging technique is more accurate, Thiessen polygons were used for burnt plots because of the scarce amount of available plots which make impossible to perform reliable variograms in the case of the kriging interpolation technique.

The R (http://www.r-project.org) package automap (Hiemstra *et al.* 2009) was used to compute the variograms and the krigings. Variogram range was fixed with the aim of obtaining a better adjustment within the proximity of the plots used. Block kriging instead of ordinary kriging was used in order to minimize prediction errors related to the large variability in the observations. Besides, kriging was applied locally with a maximum distance of 10 km, which also minimizes the sum of square error (Bivand *et al.* 2013). Thiessen polygons were computed through MiraMon software (Pons 2004).

Forest species distribution and land cover maps

Two forest maps were needed for the study according to the data coming from two different time-period inventories: 2NFI (1989) and 3NFI (2000).

Land cover and Forest map in 1989

Land cover map in 1989 (100m resolution) was obtained from Brotons *et al*. (2013). From this map, three land cover types were extracted: vulnerable covers (including forest, shrubs, alpine grass and extensive cereals), forest and shrubs.

There is no Forest Map in 1989 with the detailed information required for the analysis regarding forest structure and species composition (pure or mixed forests), so a map with the species distribution for this year was built to overlay the interpolation results from 2NFI with it.

Two reference maps were used: 1) The Forest Map 2000 (FM00): Forest tree distributions were gathered from the Spanish Forest Map (1:50 000) (Vallejo Bombin 2005) developed within the 3NFI for Catalonia from interpretation of aerial photographs, combined with pre-existing maps and fieldwork. FM00 furnishes information about tree species (up to three main species) present in each forest patch and their occupation, as well as other non forest land cover types. In FM00, pure forests were considered when the occupied area of one species per forest patch was equal or greater than 70%. This occupation threshold was before adopted by Piqué *et al*. (2011) to distinguish between mixed and monospecific forests at the landscape scale from the Spanish Forest Map and tree occupation data. The 70% occupation threshold at the landscape scale fairly matches the 80% basal area threshold used to consider monospecific forests at the stand level. 2) The Spanish Land Use Map 1980 (LUM80) (1:50 000): It was carried out in late seventies – early eighties in Catalonia by field work (MAGRAMA 1990). The LUM80 details crops and uses, distinguishing the following main cover types: unproductive, forest tree species, shrubland, pastureland and crops.

Species composition of each pixel was assumed to not change in 10 years (Brotons *et al.* 2013). Then, for unburnt pixels between 1980 and 2000, species in 1989 will be the same species present in the FM00. Information from the LUM80 was used for burnt pixels between 1989 and 2000, considering that the species in 1989 were already present in 1980. For pixels burnt between 1980 and 1989 the same procedure as for unburnt plots was followed, considering that if species are present in 2000 they were also present after fire in the 80s. This information was then overlaid with forests limits in Land Cover Map in 1989 and with the information on the interpolations from NFI2 (kriging and Thiessen polygons). Information on each species was obtained separately and, therefore, species information for each vegetation type was combined to get one unique map per vegetation type (Mediterranean pines, Oaks, and mixed forest of *Pinus halepenis* and *Quercus ilex*) for both understory medium height and basal area. Nine final raster datasets for forest structure variables were obtained at 100 m (3 for each forest cover and, 3 for forest understory and 3 for forest overstory per forest cover) (Figure 2).

Figure 2 approximately here.

Land cover and Forest map in 2000

Land cover map in 2000 was also based on (Brotons *et al.* 2013) and, therefore, vulnerable covers, forest cover and shrublabd cover were extracted from this map. The procedure was the same followed in the previous period (see above) but for burnt plots because FM00 availability. Therefore, to obtain the Forest Map in 2000, firstly was defined the species distribution of Mediterranean pines, Oaks and mixed forest of *Pinus halepensis* and *Quercus ilex* from FM00. Then, the 3NFI information obtained by the interpolation of each species through kriging and Thiessen polygons techniques was overlaid with its distribution. Finally, similarly to the previous period, 9 final rasters for forest structure variables were obtained at 100 m (3 for each forest cover and, therefore, 3 for forest understory and 3 for forest overstory).

Predictor variables

The percentage of the following variables around each ignition point within a surrounding distance of 500m and 2000m (local and landscape scale, respectively) was obtained for each considered period: 1. Vulnerable covers (%); 2. Forests (%); 3. Shrubs (%); 4. Mediterranean *Pinus* (%); 5. Oaks (%); 6. Mixed forest of *Pinus halepensis* and *Quercus ilex* (%). For the forest structure variables, mean value within the forested area of each window was calculated, obtaining the following variables: 7. *Pinus* sp. medium understory height (dm); 8. *Pinus* sp. basal area (m^2/ha); 9. Oak medium understory height (dm); 10. Oak basal area (m^2/ha); 11. Mixed forest medium understory height (dm) and 12. Mixed forest basal area (m^2/ha). The filter tool of MiraMon was used, calculating the percentage of land cover and vegetation types around each pixel, and the mean forest structure feature value around each pixel within the chosen window (500m and 2000m).

Analysis

Different models were built to understand and predict the role of different vegetation types, forest structure features and burnable land covers in the occurrence of large fires. Fire ignition points from the two time periods according to the NFI were considered together as a unique response variable. The occurrence of a fire can be modeled as a binomial outcome (i.e. de Vasconcelos *et al.* 2001; Garcia-Gonzalo *et al.* 2012) through logistic regressions (Hosmer and Lemeshow 2000). In this approach, Control/Fire (absence/presence) was the dependent variable and the other 12 variables above detailed were used as independent variables. Basal area of each forest type was introduced as a quadratic term in the modeling process, since basal area is thought to have the greatest influence on fire risk occurrence at intermediate values (Lloret *et al.* 2002).

One model for each neighborhood distance (500 and 2000m, local and landscape model, respectively) was computed as well as another combining the two distances (multiscale model).

Since control points were needed in the logistic regression, another dataset with 1000 random points within the study area limits was built. The same ignition probability was supposed throughout the whole study area although some authors (Bar-Massada *et al.* 2011) have explained the limitations of this assumption. 500 points were used for the first period and the other 500 for the second period. Ignition and control points were overlaid with the information on the predictor variables for the corresponding period, but only points with forest in the surrounding 500m were used for the study as one of the aims of the study is giving some management guidelines within forested areas.

The R package stats (R Core Team 2014) was used to built the binary logistic regression models with a logit link function. The StepAIC function in the MASS library (Venables and Ripley 2002) was used to find the best fitted model to the data following a bidirectional stepwise variable selection. The final model was selected following the Akaike Information Criterion (AIC). The AIC value represents the trade-off between model complexity and its goodness of fit. The model with the minimum AIC value between the candidate models was chosen (minimum AIC difference of 2; (Burnham and Anderson 2002)). To evaluate the prediction accuracy of the model, the Area Under the Curve (AUC) of a Receiver Operating Characteristic (ROC) curve was computed with the R package pROC (Robin *et al.* 2011). Values over 0.7, 0.8, 0.9 were considered as acceptable, good and excellent discrimination, respectively, between occurrence and non-occurrence of fire (Hosmer and Lemeshow 2000). Variation Inflaction Factor (VIF) was also calculated to check that there was not strong multicollinearity among the predictor variables (library HH) (Heiberger 2014).

Large fire risk map

Finally, the selected best candidate multiscale model was used to build a map for each period showing large fire risk occurrence. The formula (Formula 1) resulting from the logistic model was used to have a probability from 0 to 1 for fire occurrence taking into account the different variables included in the model (x_i) and regression coefficients (β_i). The map from 1989 was subtracted to the map for 2000 in order to identify changes in large fire risk occurrence from one decade to the other.

$$P = \frac{1}{1+e^{-(\beta' x)}} \text{; where } \beta' x = \beta_0 + \beta_1 \cdot x_1 + \beta_2 \cdot x_2 + \beta_3 \cdot x_3 \ldots$$

Formula 1

Results

Local and landscape partial models

When comparing the partial models some remarkable differences were found. Local model (500m model) had a smaller AIC and a greater AUC than the model at the landscape level (2000m model) (Table 1 and 2). Thus the local model had better predicting ability (greater AUC) than the model at the landscape model while being more parsimonious and explicative (lower AIC).

In the local model, the most important land covers and vegetation types influencing positively fire occurrence were the presence of shrublands and Mediterranean pines, while Oak forests had a negative influence on fire occurrence. Three forest structure variables were significant and positively correlated with fire occurrence: basal area (quadratic term was significant at $p=0.008$) and medium understory height for Mediterranean pine forests and for Oak forests. In the landscape model, shrublands and Mediterranean pine forests were significant as well as understory medium height of Mediterranean pine forests, affecting fire occurrence positively.

Tables 1 and 2 approximately here.

Multiscale model

Model prediction capacity was higher when both scales were taken into account in one unique model (higher AUC) and lower AIC values than the local and landscape models separately (Tables 1, 2 and 3). Different variables were significant when the multiscale model was computed regarding the two separate models (Table 3). As in the partial models, the presence of shrublands and Mediterranean pines around the ignition point seemed key factors for fire occurrence. The presence of Oak forest or mixed forest of *Pinus halepensis* and *Quercus ilex* 500 m around the ignition point decreased fire probability. However, the relationship between mixed forest and fire occurrence changed with distance. Near the ignition point (500m) mixed forest did not seem to favor fire occurrence but when looking at this vegetation type at a larger scale, this relationship was reversed appearing as favorable for fire to spread. The relationship between basal area of Mediterranean pines at 500m and fire occurrence was quadratic ($p=7.87e-06$).

Table 3 approximately here.

Large fire risk map

The multiscale model (Table 3) was therefore used to build a large fire risk map for forest structures in Catalonia (Figure 3) when forest was found according to land cover map of 1989 or 2000 depending on the period studied.

Figure 3 approximately here.

After subtracting both fire risk maps some changes in can be appreciated (Figure 4). In general, large fire risk has increased throughout Catalonia except in some parts at the north-east and in central Catalonia at the north of Ebro depression.

Figure 4 approximately here.

Discussion

Results are helpful to understand which forest structure by main vegetation type in Catalonia plays an important role in fire occurrence. The model obtained showed a positive relationship between fire occurrence and shrublands, Mediterranean pine forests and mixed forest, the latter at 2000m scale. Moreover, these results are valuable to propose some multiscale management strategies.

Influence of land cover types, forest composition and structure on fire risk

Partial models were separately built to understand if there were any differences in the variables affecting fire occurrence when taking a smaller or a greater area around the ignition point. However, the multiscale level has been shown to be more useful for planning strategies as it includes both scales in one model, and prediction capacity of the model is higher.

Partial models

Looking at partial models some important differences can be found. The local model was more informative (more significant variables and lower AIC) and more reliable (greater AUC) than the landscape model. There may be two reasons explaining this fact, on the one hand, local variables are more relevant than landscape variables for fire occurrence. No fire will start if there is nothing to burn around the ignition point (Pausas and Keeley 2009). On the other hand, fire seems to be more selective for certain land cover types when a fire is small (Barros and Pereira 2014).

Within these models the importance of Mediterranean pines for fire occurrence and spread was consistent. Some authors have already pointed out the importance of this vegetation type in Mediterranean ecosystems in relation to fire occurrence (see below the discussion regarding the Multiscale model). These models may be very useful to understand the role of different scales for fire occurrence but combining the information on both scales can give managers an integrative approach for management and planning at large scales.

Multiscale model

The complete model combining variables at both scales showed the relevance of land covers and forest structure around the ignition point. As expected, variables at 500m had more weight and were more represented in the model than variables at 2000m. Hence, the same explanations for partial models were applicable for the multiscale model.

In Mediterranean ecosystems shrubs are the most susceptible land cover to fire followed by forests and by cultivated areas (Nunes *et al.* 2005; Moreira *et al.* 2011; Garcia-Gonzalo *et al.* 2012). The proneness of shrubs to fire is explained because the presence of a large amount of shrubs usually implies more open conditions which means that fuel will be dryer and wind speed may be higher (Agee 1996).

Within forest types the key role of Mediterranean pine forests for fire occurrence have already been stated. Díaz-Delgado *et al*. (2004) explained that fires are larger in conifer forests and shrublands than in deciduous forests. The model implies an increase of fire occurrence probability with the increase of Mediterranean pine surface while a decrease when the surface of mixed forest or Oak forest increase. Other studies in Mediterranean ecosystems agree with that (Fernandes 2009; Moreira *et al.* 2009). One of the reasons of high fire occurrence in conifer forests is their high flammability because of their needle shaped leaves and their content in resin and essential oils (Gonzalez *et al.* 2005). Besides, pine forests usually show vertical continuity between the understory and tree canopy (Lloret *et al.* 2002).

In the relation between fire occurrence and forest variables, not only species composition was important but also forest structure (Fernandes 2009). It is noteworthy the relationship between fire risk and basal area of Mediterranean pine forests. This relationship in the model was not linear. This may be explained because when forest density increases it maintains vegetation moisture content and decreases light availability for understory to grow (Lloret *et al.* 2002; Moreira *et al.* 2011), which explains why fire occurrence in developed forests is less probable.

One of the differences between using partial models and using the multiscale model was the lack of significance of Mediterranean pines at 2000m and the appearance of mixed forests also at this scale ($p<0.05$). The lack of significance of Mediterranean pines at the landscape scale may be due to high multicolineality between the variable at both scales. The significance of mixed forest at 2000m was remarkable although its influence was opposite from the local (negative sign) to the landscape scale (positive sign). This may be explained because large fires usually do not start in this type of vegetation so the availability of this vegetation type at local scale would not be favorable for fire occurrence. However, once the fire has started the structure of this forest type may be very favorable for fire to spread because of its vertical and horizontal continuity. These forests are very vulnerable to fire because of their structure. Even if they are not very dense, its vertical continuity makes them very prone to fire. Besides, Piqué *et al.* (2011) pointed out the importance of vertical continuity in forests of *Pinus halepensis*. In this particular association for mixed forests with *Quercus ilex* the vertical continuity makes this forest type even more prone to fire because of the different heights of the two main species which increases vertical continuity (Ganteaume *et al.* 2009). Moreover, when medium height of shrubs was large, vertical continuity was also greater and vulnerability to fire was also higher.

Changes in large fire risk in Catalonia

Large fire risk occurrence in many areas of Catalonia has increased since 1989 (Figure 3). Following this trend, it could be possible that fire risk will increase in the following years due to ongoing rural abandonment which leads to land cover changes (Pausas and Fernández-Muñoz 2011). Climate conditions more favorable to fire (temperature increase and intense and recurrent drought episodes) could also enhance this situation (Piñol *et al.* 1998).

However, there are some parts in Catalonia were a decrease in large fire risk occurrence can be appreciated. This occurs in the northeastern part of Catalonia and at the northern part of Central depression. To understand this change a detailed analysis may be needed to evaluate which vegetation and land covers have changed or if any type of management has been applied (not considered here). However, some general differences between 1989 and 2000 can be found in relation to the model.

a) Decreases in Mediterranean pine forest extent around each point at northern part of central depression may have involved a decrease in fire risk occurrence (Figure 5).
b) Increases in basal area of Mediterranean pine forests at the North of Catalonia and at northern part of central depression (Figure 5). More dense forests of Mediterranean pines may be less prone to fire.
c) Decreases in medium understory height of mixed forest at northeastern Catalonia (Figure 5) which would lead to a decrease in vertical continuity making these forests less prone to fire occurrence according to the model.

Figure 5 approximately here.

From all the other variables included in the multiscale model no clear differences between one year and the other have been appreciated. However, the differences cited above were helpful to understand that changes in forest structure may be associated with changes in fire risk occurrence and showed the importance of forest management aimed to decrease large fire risk occurrence.

Management implications

In a landscape where land cover proneness and forest structure variables are actively managed, fire will spread slowly and will burn with less intensity and severity (Duguy *et al.* 2007), triggering more controllable situations to goods and people. Based on the results, three kinds of management strategies were proposed regarding to shrubland, Mediterranean pine forests and mixed forests of *Pinus halepensis* and *Quercus ilex.*

In areas where shrubs surface is large and it is combined with forest surface around, the most useful tool to decrease fire risk would be the performance of prescribed fires throughout the landscape mosaic (Keeley 2002; Baeza *et al.* 2002; Fernandes and Botelho 2004). Although it is costly and the performance time-window is small in Mediterranean climate, Conrad and Weise (1998) proposed a two step management for shrubs in Mediterranean ecosystems. It consists in low intensity management over much of the high risk area in order to improve the access for firefighters to fire and a second step of intensive management over a small part of the high risk area aimed to create corridors to expose less amount of the landscape to fires. Alternatively, the strategic planning of fire suppression resources will have the potential to become an important cost-effective fuel-reduction strategy at large spatial scale (Regos *et al.* 2014)

Fire risk concerning Mediterranean pine forests can be lowered by a widespread management and planning t strategy based on thinnings (Alvarez *et al.* 2012). This management practice has a main objective reducing basal area of the treated forest while favoring the best stems. According to the results, thinning strategy in Mediterranean forests should have the objective of lowering intermediate values of basal area (around 20m^2/ha). Pine forests with a low basal area will be less prone to fire as they do not show horizontal continuity, thus fire will have more difficulties to spread. In forests with large basal area no thinning strategy is recommended as they do not allow understory development and there is no vertical continuity. If understory is higher than 0.5m for *Pinus halepensis* or higher than 1.3m for the rest of Mediterranean pines considered (Piqué, Castellnou, *et al.* 2011), understory cleaning management should be considered.

In the case of mixed forest the management strategy advised should focus on breaking vertical continuity between aerial and understory fuel. Vertical continuity should be broken by lowering understory height and/or *Quercus ilex* height and/or pruning (Mitsopoulos and Dimitrakopoulos 2007; Piqué).

Future avenues and conclusions

The study only includes land cover and forest structure variables in order to be able to give some management strategies. However, the inclusion of climatic variables could improve model predictability. In relation with climatic variables, model prediction capacity may be improved considering ignitions occurred in climatically normal years and ignitions occurred in climatically adverse years (Brotons *et al.* 2013). More area is burnt in climatically adverse years than in normal years and, in climatically adverse years, climate may be more influent than vegetation on large fire occurrence. Thus management strategies may be more useful for climatically normal years than for severe years and management and fire suppression strategies might be different depending on the year considered. Moreover information on the fire spread type (wind fires, convective fires and topographic fires; Castellnou *et al.* 2009) can be taken into account for future research lines since fire types are differently related to vegetation and land covers.

The main land covers and vegetation types related to large fire occurrence across scales were shrublands and Mediterranean pine forests followed by mixed forests of *Pinus halepenis* and *Quercus ilex*. Forest structure variables were also good predictors. The hypothesis of an increase in large fire probability occurrence in Catalonia has been confirmed in the study. The general increase in the probability of fire occurrence in the decadal time interval considered emphasizes the relevance and novelty of this work in the increasing uncertain context associated with current and future global change.

A multiscale planning should be considered at the regional scale managing the landscape mosaic and forest structures and decreasing large fire risk. Forest management purposes in the case of Mediterranean pine forests should focus on basal area management avoiding intermediate values with subsequent dense stands (horizontal continuity), and reducing medium understory height to decrease vertical continuity and thus large fire risk. In the case of fire prone mixed forests, it would be more important to focus on vertical continuity through understory management.

Acknowledgements

Special thanks to Assu Gil, Andrea Duane and Lluís Brotons for their ideas and revisions of the final work and to the ECOLAND members (Forest Sciences Center of Catalonia; CTFC) for the data gathered for this project. Fire ignition data and fire perimeters were provided by the *Servei de Prevenció d'Incendis de la Generalitat de Catalunya*.

References

Agee JK (1996) The influence of forest structure on fire behavior. In 'Proceedings of the 17th annual forest vegetation management conference', Pp 16–18.

Alvarez A, Gracia M, Vayreda J, Retana J (2012) Patterns of fuel types and crown fire potential in Pinus halepensis forests in the Western Mediterranean Basin. *Forest Ecology and Management* **270**, 282–290.

Baeza MJ, De Luís M, Raventós J, Escarré A (2002) Factors influencing fire behaviour in shrublands of different stand ages and the implications for using prescribed burning to reduce wildfire risk. *Journal of Environmental Management* **65**(2), 199–208.

Barros AMG, Pereira JMC (2014) Wildfire Selectivity for Land Cover Type: Does Size Matter? (G Bohrer, Ed.). *PLoS ONE* **9**(1), e84760.

Bivand RS, Pebesma E, Gómez-Rubio V (2013) 'Applied Spatial Data Analysis with R.' (Springer: New York)

Bond WJ, Keeley JE (2005) Fire as a global 'herbivore': the ecology and evolution of flammable ecosystems. *Trends in Ecology & Evolution* **20**(7), 387–394.

Bond WJ, Woodward FI, Midgley GF (2005) The global distribution of ecosystems in a world without fire. *New Phytologist* **165**(2), 525–538.

Brotons L, Aquilué N, de Cáceres M, Fortin M-J, Fall A (2013) How Fire History, Fire Suppression Practices and Climate Change Affect Wildfire Regimes in Mediterranean Landscapes (G Bohrer, Ed.). *PLoS ONE* **8**(5), e62392.

Burnham KP, Anderson RD (2002) 'Model selection and multimodel inference. A Practical Information-Theoretic Approach.' (Springer: New York).

Burriel JA, Ibáñez JJ, Pons X (2001) El Mapa de Cubiertas del Suelo de Cataluña: Herramienta para la gestión y la planificación territorial. In 'Congresos Forestales'.

Castellnou M, Miralles M, Pages J, Pique M (2009) Tipificación de los incendios forestales de Cataluña. Elaboración del mapa de incendios de diseño como herramienta para la gestión forestal. In 'Proceedings of the 5th Congreso Forestal Español. Ávila, Spain'.

Conard SG, Weise DR, others (1998) Management of fire regime, fuels, and fire effects in southern California chaparral: lessons from the past and thoughts for the future. In 'Tall Timbers Ecology Conference Proceedings', Pp 342–350.

Cui W, Perera AH (2008) What do we know about forest fire size distribution, and why is this knowledge useful for forest management? *International Journal of Wildland Fire* **17**(2), 234–244.

Debussche DL, Lepart J, Darvieux A (1999) Mediterranean landscapes changes: The ancient postcard evidence. *Global Ecology and Biogeography* **8**, 3–16.

Díaz-Delgado R, Lloret F, Pons X (2004) Spatial patterns of fire occurrence in Catalonia, NE, Spain. *Landscape Ecology* **19**(7), 731–745.

Duane A, Piqué M, Castellnou M, Brotons L (Submitted) Predictive modelling of fire occurrences from different fire spread patterns in Mediterranean landscape. *Wildland fire*.

Duguy B, Alloza JA, Röder A, Vallejo R, Pastor F (2007) Modelling the effects of landscape fuel treatments on fire growth and behaviour in a Mediterranean landscape (eastern Spain). *International Journal of Wildland Fire* **16**(5), 619.

Fernandes PM (2009) Combining forest structure data and fuel modelling to classify fire hazard in Portugal. *Annals of Forest Science* **66**(4), 1–9.

Fernandes P, Botelho H (2004) Analysis of the prescribed burning practice in the pine forest of northwestern Portugal. *Journal of Environmental Management* **70**(1), 15–26.

Finney MA (2001) Design of regular landscape fuel treatment patterns for modifying fire growth and behavior. *Forest Science* **47**(2), 219–228.

Finney MA (2005) The challenge of quantitative risk analysis for wildland fire. *Forest Ecology and Management* **211**(1), 97–108.

Ganteaume A, Marielle J, Corinne L-M, Thomas C, Laurent B (2009) Fuel characterization and effects of wildfire recurrence on vegetation structure on limestone soils in southeastern France. *Forest ecology and management* **258**, S15–S23.

Garcia-Gonzalo J, Zubizarreta-Gerendiain A, Ricardo A, Marques S, Botequim B, Borges JG, Oliveira MM, Margarida T, Pereira JMC (2012) Modelling wildfire risk in pure and mixed forest stands in Portugal.

Giralt E (1990) L'Agricultura. 'Història Econòmica de la Catalunya Contemporanea. Població i Agricultura. Vol.2. Enciclopèdia Catalana'. (Eds J Benavente, E Giralt, R Nicolau) pp.121–309. (Barcelona, Spain).

Gonzalez JR, Palahí M, Pukkala T (2005) Integrating fire risk considerations in forest management planning in Spain–a landscape level perspective. *Landscape Ecology* **20**(8), 957–970.

Gonzalez JR, Palahi M, Trasobares A, Pukkala T (2006) A fire probability model for forest stands in Catalonia (north-east Spain). *Annals of Forest Science* **63**(2), 169–176.

Heiberger RM (2014) 'HH:Statistical Analysis and Data Display: Heiberger and Holland.'

Hiemstra PH, Pebesma EJ, Twenhofel CJW, Heuvelink GBM (2009) Real-time automatic interpolation of ambient gamma dose rates from the Dutch Radioactivity Monitoring Network. *Computers & Geosciences* **35**(8), .

Hirsch K, Kafka V, Tymstra C, McAlpine R, Hawkes B, Stegehuis H, Quintilio S, Gauthier S, Peck K (2001) Fire-smart forest management: a pragmatic approach to sustainable forest management in fire-dominated ecosystems. *The Forestry Chronicle* **77**(2), 357–363.

Hosmer DW Jr, Lemeshow S (2000) 'Applied Logistic Regression.' (John Wiley & Sons: New York).

Keeley JE (2002) Fire management of California shrubland landscapes. *Environmental Management* **29**(3), 395–408.

Krawchuk MA, Moritz MA, Parisien M-A, Van Dorn J, Hayhoe K (2009) Global Pyrogeography: the Current and Future Distribution of Wildfire (J Chave, Ed.). *PLoS ONE* **4**(4), e5102.

Lloret F (1996) El foc en un context mediterrani. 'Ecologia del foc'. (Ed J Terradas) pp.41–50. (Edicions Proa, S.A.: Barcelona).

Lloret F, Calvo E, Pons X, Díaz-Delgado R (2002) Wildfires and landscape patterns in the Eastern Iberian Peninsula. *Landscape Ecology* **17**(8), 745–759.

MAGRAMA (1990) Mapa de cultivos y aprovechamientos.

Bar-Massada A, Syphard AD, Hawbaker TJ, Stewart SI, Radeloff VC (2011) Effects of ignition location models on the burn patterns of simulated wildfires. *Environmental Modelling & Software* **26**(5), 583–592.

Miller C, Urban DL (2000) Connectivity of forest fuels and surface fire regimes. *Landscape Ecology* **15**(2), 145–154.

Mitsopoulos ID, Dimitrakopoulos AP (2007) Canopy fuel characteristics and potential crown fire behavior in Aleppo pine (Pinus halepensis Mill.) forests. *Annals of Forest Science* **64**(3), 287–299.

Moreira F, Vaz P, Catry F, Silva JS (2009) Regional variations in wildfire susceptibility of land-cover types in Portugal: implications for landscape management to minimize fire hazard. *International Journal of Wildland Fire* **18**(5), 563–574.

Moreira F, Viedma O, Arianoutsou M, Curt T, Koutsias N, Rigolot E, Barbati A, Corona P, Vaz P, Xanthopoulos G, Mouillot F, Bilgili E (2011) Landscape – wildfire interactions in southern Europe: Implications for landscape management. *Journal of Environmental Management* **92**(10), 2389–2402.

Ninyerola M, Pons X, Roure JM (2000) A methodological approach of climatological modelling of air temperature and precipitation through GIS techniques. *International Journal of Climatology* **20**(14), 1823–1841.

Nunes MC, Vasconcelos MJ, Pereira JM, Dasgupta N, Alldredge RJ, Rego FC (2005) Land cover type and fire in Portugal: do fires burn land cover selectively? *Landscape Ecology* **20**(6), 661–673.

Pausas JG (2004) Changes in fire and climate in the eastern Iberian Peninsula (Mediterranean basin). *Climatic Change* **63**(3), 337–350.

Pausas JG, Fernández-Muñoz S (2011) Fire regime changes in the Western Mediterranean Basin: from fuel-limited to drought-driven fire regime. *Climatic Change* **110**(1-2), 215–226.

Pausas JG, Keeley JE (2009) A burning story: the role of fire in the history of life. *BioScience* **59**(7), 593–601.

Pausas JG, Paula S (2012) Fuel shapes the fire–climate relationship: evidence from Mediterranean ecosystems. *Global Ecology and Biogeography* **21**, 1074–1082.

Piñol J, Terradas J, Lloret F (1998) Climate warming, wildfire hazard, and wildfire occurrence in coastal eastern Spain. *Climatic change* **38**(3), 345–357.

Piqué M, Castellnou M, Valor T, Larrañaga A, Miralles M, Cervera T (2011) Integraciò del risc de grans incendis forestals (GIF) en la gestió forestal: Incendis tipus i vulnerabilitat de les estructures forestals al foc de capçades.

Piqué M, Vericat P, Cervera T, Baiges T, Farriol R (2011) Tipologies forestals arbrades.

Pons X (2004) 'MiraMon. Sistema de'Informació Geogràfica i software de Teledetecció.' (Centre de Reserca Ecològica i Aplicacions Forestals, CREAF: Bellaterra)

Pyne SJ, Andrews PL, Laven RD, others (1996) 'Introduction to wildland fire.' (John Wiley and Sons: New York) .

R Core Team (2014) R: A language and environment for statistical computing. *R Foundation for Statistical Computing, Viena*.

Regos A, Aquilué N, Retana J, De Cáceres M, Brotons L (2014) Using unplanned fires to help suppressing future large fires in mediterranean forests. *PloS one* **9**(4), e94906.

Robin X, Turck N, Hainard A, Tiberti N, Lisacek F, Sanchez JC, Müller M (2011) pROC: an open-source package for R and S+ to analyze and compare ROC curves. *BMC Bioinformatics* **12**, 77.

Rothermel RC (1983) How to predict the spread and intensity of forest and range fires. *USDA For Serv*(INT-GRT-143).

Tercer Inventario Forestal Nacional (1997-2007) (2005) (Ministerio de Medio Ambiente: Madrid)

Terradas J, Piñol Pascual J, Lloret Maya F (1998) Risk factors in wildfires along the Mediterranean coast of the Iberian Peninsula. 'Fire management and landscape ecology'. pp.297–304. (International Association of Wildland Fire: Washington).

Terradas J, Rodà F (2004) 'Els boscos de Catalunya: estructura, dinàmica i funcionament.' (Departament de Medi Ambient i Habitatge).

Thonicke K, Venevsky S, Sitch S, Cramer W (2001) The role of fire disturbance for global vegetation dynamics: coupling fire into a Dynamic Global Vegetation Model. *Global Ecology and Biogeography* **10**(6), 661–677.

Torras O, Saura S (2008) Effects of silvicultural treatments on forest biodiversity indicators in the Mediterranean. *Forest Ecology and Management* **255**(8), 3322–3330.

Vallejo Bombin R (2005) El Mapa Forestal de España escala 1: 50.000 (MFE50) como base del tercer Inventario Forestal Nacional. *Cuadernos de la Sociedad Española de Ciencias Forestales* 205–210.

De Vasconcelos MJP, Silva S, Tome M, Alvim M, Pereira JC (2001) Spatial prediction of fire ignition probabilities: comparing logistic regression and neural networks. *Photogrammetric Engineering and Remote Sensing* **67**(1), 73–81.

Venables WN, Ripley BD (2002) 'Modern Applied Statistics.' (Springer: New York)

Villaescusa R, Díaz R (Eds) (1998) 'Segundo Inventario Forestal Nacional (1986-1996).' (España. Ministerio de Medio Ambiente-ICONA: Madrid)

Figures

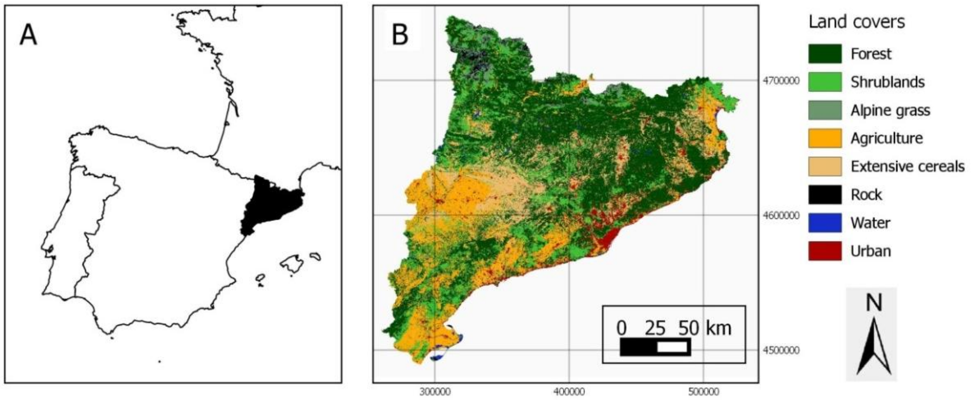

Figure 1. A. Location of Catalonia in Spain. Scale: 1: 20000000 B. Land cover map of Catalonia. UTM projection 31N Datum ETRS89.

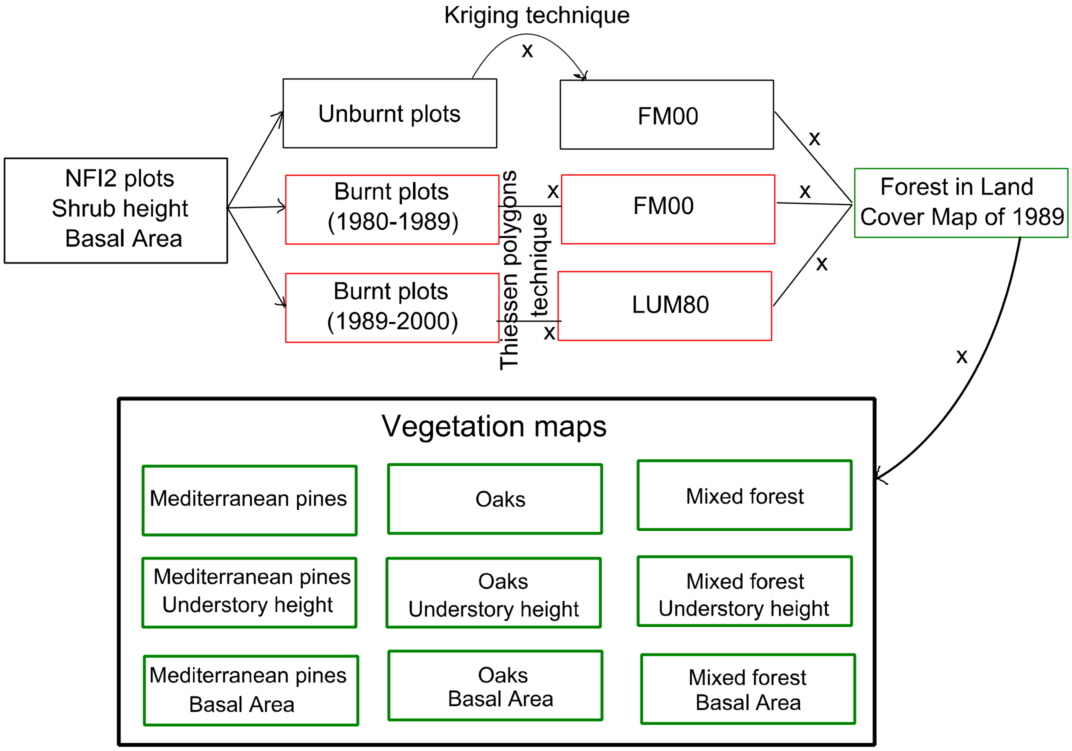

Figure 2. Schema for the realization of vegetation maps in 1989 using forest structure data from NFI2 plots.

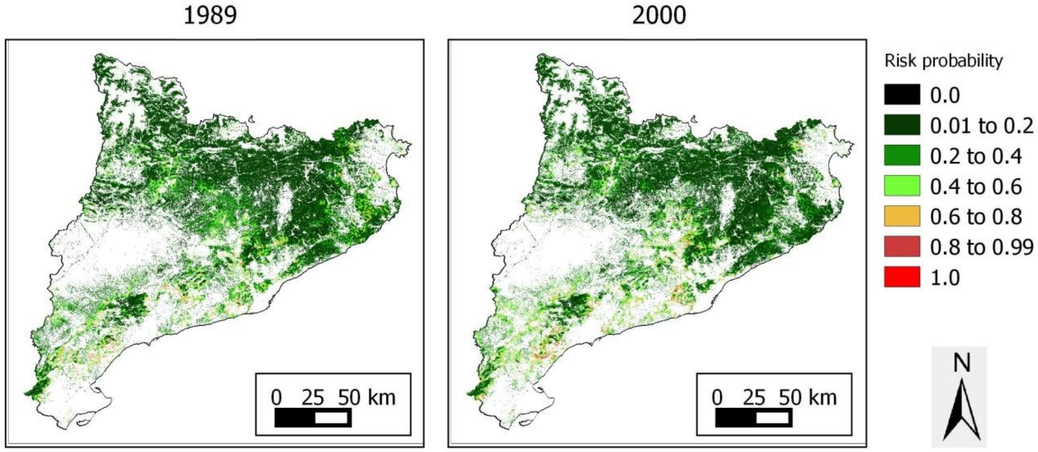

Figure 3. Large fire risk map for the two time periods considered according to NFI data availability.

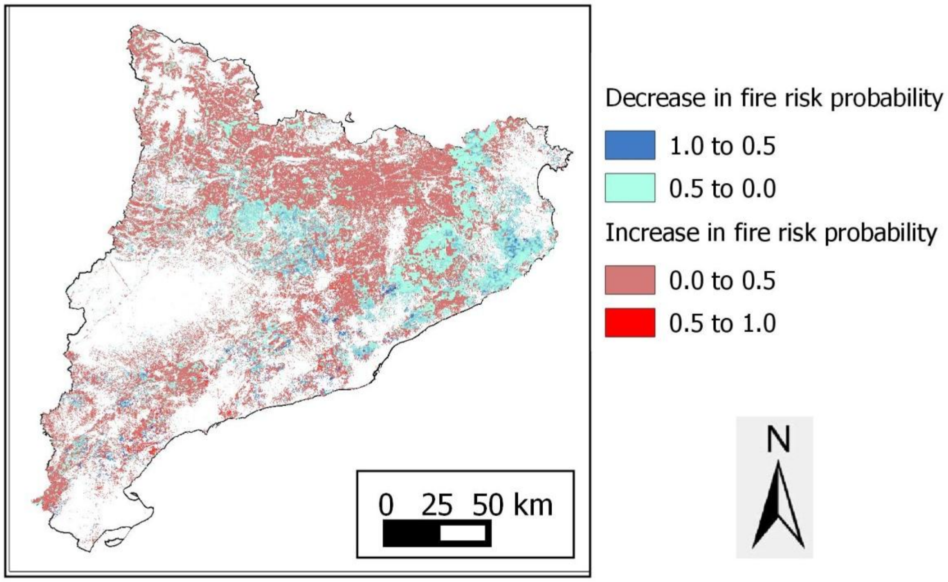

Figure 4. Changes in probability of large fire risk occurrence between the two periods considered according to NFI data availability.

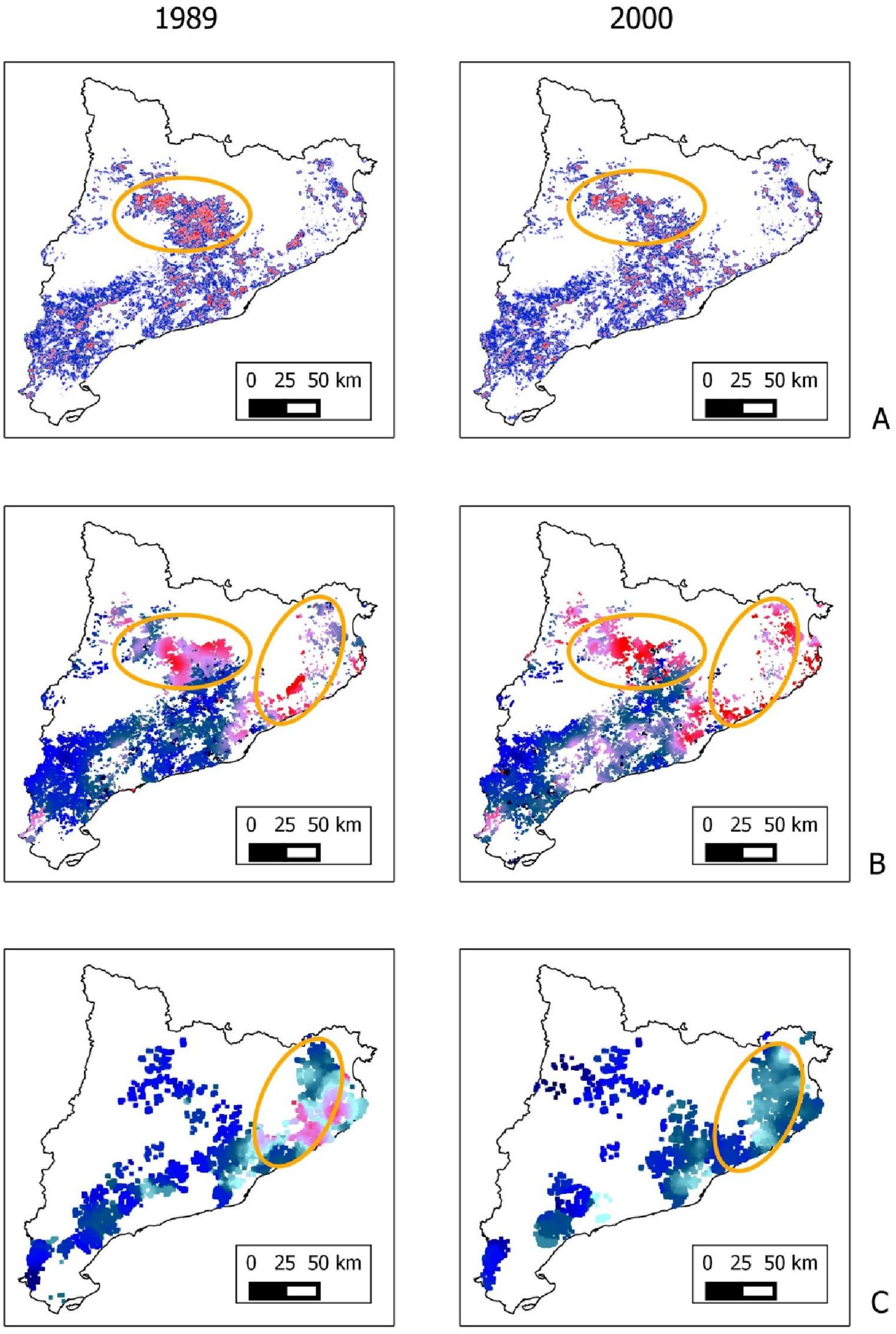

Figure 5. A) Mediterranean pine forests distribution. B) Basal Area of Mediterranean pines distribution. C) Medium understory height of mixed forests. Lower values in dark blue and higher values in red (from 0 to 100% in A; from 0 to 35m^2/ha in B; from 0 to 30dm in C).

Tables

	Estimate	P value
Intercept	-2.974	<2e-16
Shrubs cover	2.957	6.89e-14
Mediterranean Pines	1.066	0.010
Mediterranean Pines Basal Area	0.103	0.091
Mediterranean Pines Square basal area	-0.007	0.008
Mediterranean Pines Understory height	0.104	0.004
Oaks	-3.130	0.014
Oaks Understoy height	0.113	0.0001
AIC=947.43 **AUC**=0.756		

Table 1. Local scale model predicting fire occurrence. Independent variables were computed 500m around ignition/control points.

	Estimate	P value
Intercept	-2.773	<2e-16
Shrubs cover	3.135	8.60e-16
Mediterranean Pines	1.859	3.47e-05
Mediterranean Pines Understory height	0.073	0.0007
AIC=984.17 **AUC**=0.730		

Table 2. Landscape scale model predicting fire occurrence. Independent variables were computed 2000m around ignition/control points.

Intercept	-3.341	<2e-16
Shrubs cover (500m)	2.168	0.0002
Mediterranean Pines (500m)	1.333	0.002
Mediterranean Pines Basal Area (500m)	0.210	1.83e-06
Mediterranean Pines Square basal area (500m)	-0.011	7.87e-06
Mixed forest (500m)	-3.509	0.001
Oaks (500m)	-3.240	0.013
Oaks Understory height (500m)	0.100	0.001
Shrubs cover (2000m)	1.816	0.004
Mixed forest (2000m)	3.466	0.011
Mixed forest Understory height (2000m)	0.075	6.91e-05
AIC=926.61 **AUC**=0.773		

Table 3. Multiscale model predicting fire occurrence. Independent variables were computed 500m and 2000m around ignition/control points.