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Assessing wildfire occurrence probability in *Pinus pinaster* Ait. stands in Portugal

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Abstract

Maritime pine (*Pinus pinaster* Ait.) is an important conifer from the western Mediterranean Basin extending over 22% of the forest area in Portugal. In the last three decades nearly 4% of Maritime pine area has been burned by wildfires. Yet no wildfire occurrence probability models are available and forest and fire management planning activities are thus carried out mostly independently of each other. This paper presents research to address this gap. Specifically, it presents a model to assess wildfire occurrence probability in regular and pure Maritime pine stands in Portugal. Emphasis was in developing a model based on easily available inventory data so that it might be useful to forest managers. For that purpose, data from the last two Portuguese National Forest Inventories (NFI) and data from wildfire perimeters in the years from 1998 to 2004 and from 2006 to 2007 were used. A binary logistic regression model was build using biometric data from the NFI. Biometric data included indicators that might be changed by operations prescribed in forest planning. Results showed that the probability of wildfire occurrence in a stand increases in stand located at steeper slopes and with high shrubs load while it decreases with precipitation and with stand basal area. These results are instrumental for assessing the impact of forest management options on wildfire probability thus helping forest managers to reduce the risk of wildfires.

Key words: forest management; risk; fire occurrence model; *Pinus pinaster* Ait.

Resumen

Evaluación de la probabilidad de ocurrencia de fuegos en rodales de *Pinus pinaster* en Portugal

El articulo presenta un modelo para evaluar la probabilidad de ocurrencia de incendios en masas regulares y puras de *Pinus pinaster* en Portugal. Se desarrolla un modelo basado en datos de inventario fácilmente disponibles de tal forma que pueda ser una herramienta útil para los gestores forestales. Los datos proceden de los dos Inventarios Nacionales de Portugal (NFI) y de los datos de los parámetros de incendios forestales durante los años 1998-2004 y de 2006 a 2007. Se ha utilizado un modelo de regresión logística binarias utilizando datos biométricos del NFI. Los datos biométricos incluyen indicadores que puedan ser cambios en las operaciones prescritas en los planes forestales. Los resultados muestran que la probabilidad de ocurrencia de incendios en un rodal aumenta en rodales localizados en grandes pendientes y con una carga alta de matorrales, mientras que decrece con la precipitación y con el área basimétrica. Estos resultados son instrumentos para evaluar el impacto de las opciones de gestión forestal en la probabilidad de incendios ayudando por tanto a los gestores a reducir el riesgo de incendio.

Palabras clave: gestion forestal, riesgo, modelo de ocurrencia de incendios, *Pinus pinaster* Ait.

Introduction

In Portugal, nearly 40% of the country's territory was burned in the last three decades (Marques *et al.*, 2011). These wildfires had a substantial impact in the forested landscape configuration and composition. For example, the relative importance of the maritime pine area decreased from 30% to 22% of the total forest area in the period from 1995 to 2006 (DGRF, 2006). In the last ten years wildfires burned about 26,000 hectares,

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which is around 3.7% of total maritime pine stands (NIR, 2009). Maritime pine is still the most important timber producing species in Portugal and is mainly managed as even-aged plantations with a clear-cut harvest. Forest owners and forest managers need information that may help them develop management plans to minimize wildfire risk.

The term *risk* has been defined in several ways in the natural hazard literature. According to the definitions proposed by Hardy (2005), fire risk is defined as the chance that a fire might start in a context characterized by both natural and human causes (e.g. ignitions) and fire hazard as the potential fire behavior for a fuel type, regardless of the fuel type's weather-influenced fuel moisture content. González *et al.* (2006) proposed the term endogenous risk and Jactel *et al.* (2009) proposed the term hazard likelihood. We will refer to the term risk as the probability of a stand to be affected by a wildfire (i.e. probability of occurrence).

Many authors have studied the impact on wildfire risk of variables that are uncontrollable by forest managers such as weather variables (Chuvieco *et al.*, 2010; Durão *et al.*, 2010; Finney, 2005; Pereira *et al.*, 2005; Preisler *et al.*, 2004), physiographical variables (Carreiras and Pereira, 2006; Finney, 2005; González *et al.*, 2006; Marques *et al.*, 2011; Moreira *et al.*, 2009; Preisler *et al.*, 2004) and wildfire ignition in Portugal (Catry *et al.*, 2009; Vasconcelos *et al.*, 2001). However these models are not forest planning oriented. Yet the effectiveness of forest management depends on the availability of information about the impact on wildfire occurrence of biometric variables that are controllable by forest managers.

The forest cover type, the presence of multi-layered or young stands and the fuel load have a substantial impact on the probability of wildfire occurrence (Castro *et al.*, 2003; Ceccato *et al.*, 2002; Cumming, 2001; Reed, 1994; Velez, 1990). Modification of any of these fuel strata by silvicultural operations will thus have implications on wildfire occurrence (Jactel *et al.*, 2009; Peterson *et al.*, 2005). Thus in order to address wildfire risk, forest managers need information about the impact of "controllable" variables such as stand density, species composition, fuel availability at surface level (i.e. shrubs) and vertical structure of the stand on the probability of fire occurrence (Cumming, 2001; Finney, 2005). In this framework, González *et al.* (2006) developed a fire probability model for forest stands in Catalonia with biometric variables that may be readily available in order to include them in forest planning optimization to minimize risk (González-Olabarria *et al.*, 2008). In Portugal such models are not yet available and would help reverse current trends of maritime pine forestry.

The successful management of maritime pine in fire-prone regions is thus a challenging task that calls for the integration of wildfire risk in forest management planning. This research addresses this integration need by developing a management-oriented model (i.e. using easily measurable biometric variables) that may be able to predict the effects of management options (e.g. silvicultural treatments) on the probability of wildfire occurrence in pure and even-aged maritime pine stands.

Materials and methods

Materials

The assessment of wildfire risk probability in pine stands was based on historical fire information from 1998 to 2004 and 2006 to 2007. The fire data consisted of all perimeters of wildfires larger than 5 hectares, obtained by semi-automated classification of high-resolution remote sensing data (i.e., Landsat Multi-Spectral Scanner (MSS), Landsat Thematic Mapper (TM), and Landsat Enhanced TM+), that occurred in the two periods. In total 9,960 and 2,313 fire perimeters were identified in the first and in the second period, respectively. These wildfires burned over 150,000 ha.

The official wildfire database from the Portuguese Forest Service (AFN) that stores the starting coordinates (ignition) of wildfires was further used. For each year, a buffer around each ignition point was created with the minimum size needed to cover all burned plots in that year (Fig.1).

Biometric and environmental data considered for further analysis was acquired in 233 and 500 pure and even-aged maritime pine plots out of the 2,336 and 12,000 plots measured in the National Forest Inventories (NFI) carried out in the periods from 1995 to 1998 and 2005 to 2006, respectively. These plots were identified by overlapping NFI maps and wildfire perimeters. The status (burned/unburned) of each plot and the fire event were also recorded.

Our research extended the approach of González *et al.* (2006) in order to obtain an annual probability of wildfire. For that purpose an estimate of the bio-

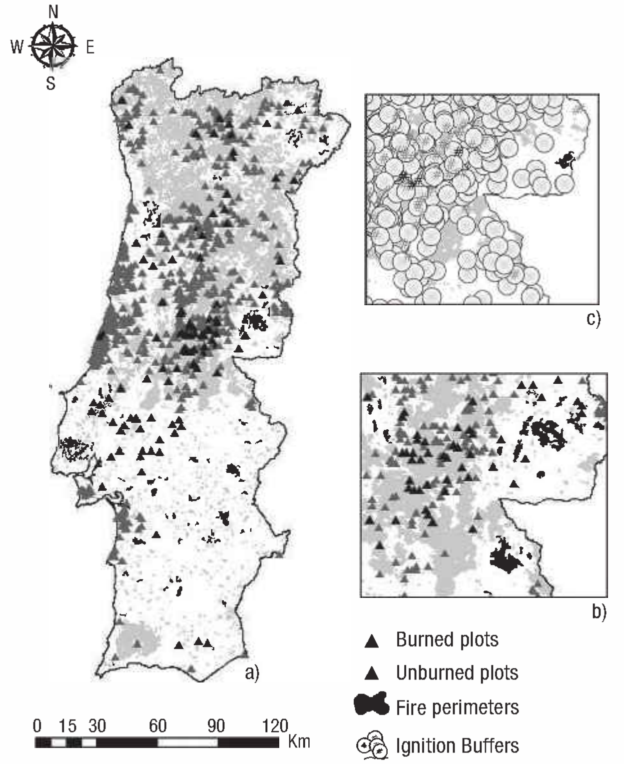

Figure 1. The map displays the fire perimeters occurred in Portugal during two periods: 1997-2004 and 2005-2007 and plots of pure / even-aged Maritime pine plots (a), a part of the data acquisition national forest inventory (NFI) plots used in the study (b), elimination of unburned plots due to the large distance to ignition points (c).

metric variables of each plot in each year in the period ranging from the inventory date to either the fire event date or the date of the next inventory was needed (Table 1). Thus, the stand-level growth and yield model, DUNAS (Falcão, 1997) was used to project Maritime pine growth and to estimate biometric variables in each plot. For modeling purposes a categorical variable was created for each observation and year with the value of 0 (fire did not occur) or 1 (fire did occur), (Table 1). If the stand burned a dichotomous variable (1) was assigned and the projection was stopped. If the stand did not burn, a value 0 was assigned and a projection done for the next year. As a consequence of the growth projections over time, one plot from the NFI resulted in several observations. The year 2005 was not included because we considered that projecting the forest growth over more than 6 years might lead to errors due to forest cover changes (e.g. harvests).

The maps with the buffers were overlaid with the maps with the Maritime pine observations (i.e. NFI plots estimated over time) (Fig. 1). Only observations within the ignition buffers were taken into account for modeling purposes. This methodology allowed us to eliminate observations that were not affected by a wildfire because there was no ignition point around. In total, 1945 observations estimated from the 733 NFI plots were used to fit the model, 66 of which were burned plots (Table 2).

Wildfire occurrence depends on further environmental variables (Catry *et al.*, 2008, 2009; Marques *et al.*, 2011; Wittenberg and Malkinson, 2009). The altitude of each plot was obtained from the country's Digital Terrain Model (DTM). The weather information was based on the same data from Tomé *et al.*

Table 1. Characterization of inventory plots in each year of the study period. The DUNAS growth and yield model (Falcão, 1997) was used to project all state variables in each 1998 NFI plot. If the stand burned a dichotomous variable (1) was assigned and the projection was stopped. If the stand did not burn, a value 0 was assigned and a projection done for the next year. Projections stopped in year 2004 as another inventory was available for year 2005

Inventory plot ID	Inventory 1998		Projection 1999		....		Projection 2004		Number of Observations per plot
	State Variables	Status	State Variables	Status	State Variables	Status	State Variables	Status	
1	X	0	X	1	…	…	–	–	2
2	X	0	X	0	…	…	X	1	7
3	X	0	X	0	…	…	X	1	7
4	X	0	X	0	…	…	X	0	7
5	X	1	X	–	…	…	–	–	1
6	X	0	X	0	…	…	X	0	7
7	X	0	X	0	…	…	X	0	7
…	…	…	…	…	…	…	…	…	…
233	X	0	X	1	…	…	X	–	2

…: indicates missing rows and columns. –: Indicates no projection done for that year.

Table 2. Number of *Pinus pinaster* plots recorded as burned and unburned each year in the studied periods and statistics for the fitting dataset (Continuous variables)

Number of *Pinus pinaster* plots recorded

Year	1998	1999	2000	2001	2002	2003	2004	2006	2007
Unburned	213	173	168	134	187	149	81	358	416
Burned	7	2	5	4	9	31	1	4	3

Statistics for the fitting dataset (Continuous variables)

Variables	Description	Max		Mean		Min	
		Unburned	Burned	Unburned	Burned	Unburned	Burned
Slope (°)	Terrain slope	117	34	9.2	12	0	0
Altitude (m)	Terrain altitude	1,285	1,135	349.7	499.9	5	35
Age (years)	Stand age	110.7	79	38	33.8	0	2
Hdom (m)	Stand dominant height	46	46	16	15.1	3.8	4.5
N (N.trees ha^{-1})	Stand density	3,658	1,260	517	405	20	18
Temperature (°C)	Mean Temperature	21.3	16. 8	13.4	12.9	4.9	8.8
Precipitation (days/year)	Precipitation days	152	144	107	100	65	75
Dg (cm)	Quadratic mean diameter	65.7	116.1	23.1	24.9	7. 8	7.9
G ($m^2 ha^{-1}$)	Stand basal area	59.2	54.9	19.2	15.2	0.1	0.3
G/dg	Stand structure (regular/irregular)	3.3	1.9	0.8	0.6	0.01	0.03
Shrubs Biomass (Mg ha^{-1})	Shrub biomass load	17.7	14.8	6.9	8.7	0	0

(2006), collected from Atlas do Ambiente, which is a grid of 23,121 points with climate information characterized in terms of: air humidity (%), insolation (hours), solar radiation (kcal cm^{-2}), average air temperature (°C), runoff (mm), evapotranspiration (mm), days of precipitation exceeding 0.1 mm and total rainfall.

In order to further characterize the plot at the time of wildfire occurrence, it was also necessary to project shrub growth in the period ranging from the inventory year to the wildfire occurrence year or to the next inventory. For that purpose, equation 1 was used to simulate the shrub biomass accumulation (Botequim *et al.*, 2009).

$$SBiom = (32.75 - 0.0239 \times Resp - 0.1528 \times G) \times \times (1 - exp^{(-(0.00108 \times Resp + 0.00249 \times T) \times tshrubs)}) \quad \text{[Eq.1]}$$

Where *SBiom* is the total amount of shrubs (Mg ha^{-1}) on the moment *t*, *Resp* is the percentage of resprouters in the stand (%), G is the basal area of the trees on the stand (m^2 ha^{-1}), T is mean temperature (°C) and tshrubs is the accumulation of time since the last fire, considered the age of the shrubs (years). This equation was developed using data from 421 plots obtained in the framework of the two NFIs. Both NFIs include variables describing the vertical structure and composition on the inventoried forests and give information on shrub vegetation cover and shrub height. Those measurements are from temporary plots, measured only once. Using this information and based on the methodology of the NFI shrub biomass (Mg ha^{-1}), of the stands was estimated using Eq.2.

$$SBiom = (h \times cov \times 100) \times bulkdens \quad \text{[Eq. 2]}$$

where h is the shrub height (m), cov is the percentage of the stand covered by shrubs and equals 100 when coverage is total and 0 when there is no presence of shrubs, bulk dens (kg m^{-3}) is defined as the fuel load (dry weight) per unit volume of vegetation (Rothermel, 1972; Brown, 1971).

Methods

The occurrence of wildfire in a stand over a given period of time is a binomial outcome that may be modeled by Binary logistic regression (Hosmer and Lemeshow, 2000). This modeling approach assigns ‘1’ to the event of wildfire occurrence and a ‘0’ to the no wildfire occurrence event and it was used in order to assess the impact of both biometric and environmental on the probability of wildfire occurrence in maritime pine stands, a wide set of explanatory variables was explored through extensive testing (Table 2).

As a first step, an analysis of the relationship of each individual independent variable with response variables was performed for a preliminary assessment of the relative importance of each variable on wildfire occurrence probability in maritime pine stands. The final multivariate model is obtained using stepwise regression on the training set combined with an understanding of the process of wildfire risk probability. Thus, the final model building considered ecological consistency, management relevance and its statistical significance (i.e. 0.05 significance level).

The different models were compared using the Akaike Information Criterion (AIC) (Burnham and Anderson, 2003; Silva *et al.*, 2009), and the one with lowest AIC considered the more parsimonious. Model performance was assessed through the likehood-ratio statistic (full model χ^2) and by calculating the area under the Receiver Operating Characteristics (ROC) curve (Hosmer and Lemeshow, 2000; Shapiro, 1999). For the multivariate model, Wald statistic test was also computed, for each selected variable. Thus the wildfire risk occurrence model in maritime pine stands was developed using a procedure that estimates the parameters of the logistic equation with maximum likelihood methods using PROC Logistic procedure of SAS 9.2 (SAS Institute, Cary, NC). Collinearity was assessed by adding new variables to the model and observing the effect on the slope coefficients and the estimated standard errors (Hosmer and Lemeshow, 2000).

The logistic model predicts a probability of an occurrence ranging continuously between 0 and 1. For certain applications a dichotomous variable is needed (e.g. burned or not burned) and a cut-point must be defined and compared to each estimated probability (Hosmer and Lemeshow, 2000). Different selection criteria have been proposed by some authors as Ryan and Reinhardt (1988), Hosmer and Lemeshow (2000), Monserud and Sterba (1999) and Neter and Maynes (1970). If the use of the model is to calculate the probability of wildfire occurrence a cut-point is not needed. However, we calculated a cut-point as an indicative value for other studies. This value was calculated using the Hosmer and Lemeshow method that consists in finding the value where the sensitivity curve and the specificity curve intersect. Classification classification rates (CCR) associated with different criteria to define cut-points also help select the best cut-point value.

Results

Fire probability model

The logistic model selected to predict wildfire occurrence is:

$$Pburn = \frac{1}{1 + e^{-(-2.0216 + 0.0204 \times Slp + 0.0597 \times SBiom - 0.0153 \times Prec - 0.5856 \frac{G}{dg}}} \text{ [Eq. 3]}$$

Where Slp is slope (degrees), SBiom is the total biomass of shrubs (Mg ha–1), Prec is the number of days with precipitation higher than 1 mm, G is the stand basal area ($m^2\,ha^{-1}$) and dg is the quadratic mean diameter of the stand (cm). The predictor *G*/dg is non-linearly related to the number of trees per hectare ($m^2\,ha^{-1}\,cm^{-1}$), it provides information about density and tree sizes.

All coefficients in Eq, 3 were significant, at least at the 0.05% level as judged by the Wald $\chi 2$ statistic (Hosmer and Lemeshow, 2000). The model predicted the right outcome (fire occurrence) in the case of 66.3% of the observations. The adequacy of the model was further assessed by the analysis of the ROC curve from the logistic model (area under the ROC curve of 0.677). Hosmer and Lemeshow goodness-of-fit test statistics were calculated and examining the partition in this test we can see that few models had low expected frequencies, thus suggesting that the p-values are accurate enough to support the hypothesis that the model fits. The assessment showed no collinearity among variables included in the model.

According to the equation 3 the model indicates that higher increase of slope and shrubs biomass increases the probability of a Maritime Pine stand to be burned. On the contrary the increase of precipitation and G/dg in a stand will decrease this probability (Fig. 2).

The odds ratio was further used to help interpret results, which is a more intuitive and easily understood way to capture the relationship between the independent and dependent variables. (Hosmer and Lemeshow, 2000; Kleinbaum, 1994). The odds ratio can be interpreted as the change in the odds for any increase of one unit in the parameter analyzed. However, the change in odds for some amount other than one unit is often of greater interest. Exponentiation of the parameter estimate(s) for the independent variable(s) in the model by the number c yields the odds ratio, where c is the increase in the corresponding independent variable.

From the analyses conducted it can be interpreted that an increase of 5 degrees in slope, would increase the probability of a stand to be burned in 1.107 times.

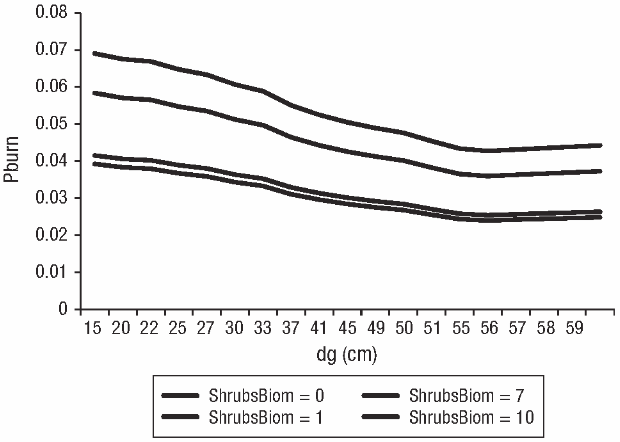

Figure 2. Effect of shrubs biomass and G/dg on the proportion of fire occurrence probability in stand with 93 days of precipitation per year.

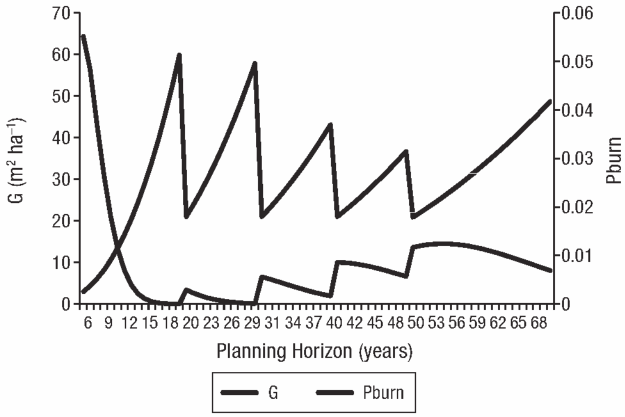

Figure 3. Effects of thinning and shrub cleanings on the probability of wildfire occurrence depending on a typical maritime pine stand located in central Portugal and assuming constant probability of ignition.

The chance of a stand to burn also increases in 1.062 times if the total biomass of shrubs increases one Mg per ha–1. On other hand, a increase if 1 one day of precipitation higher than 0,01 mm in a maritime pine stand, would decrease this probability in 0.985 times, but a increase in 5 days would decrease the risk to be burned in 0.9263 times. The odds for different combination of variables were checked for the predictor G/dg, being the effect of variation both variables (i.e. G and dg) analyzed. An increase in 8 cm of dg on a stand with 20 $m^2 ha^{-1}$ of G decreases 0.2313 times the fire hazard probability whereas an increase in 20 cm of dg for the same stand decreases fire probability in 0.5568 times. The effect of increasing G in 10 $m^2 ha^{-1}$ on a stand with a dg of 30 cm, would decrease the fire probability 0.8227 times, but an increase of 25 $m^2 ha^{-1}$ would decrease this probability 0.6139 times.

Because for some application there might be the need to transform the annual probability in a dichotomous variable (i.e. burns or does not burn), a cut-point was calculated (0.035). Using this value led to a CCR of 62.3% and the percentage of stands classified as having mortality was 31%. According to the chosen cut-point, the frequency table was calculated and from the analysis, this model predicts well 62.2% of the burned plots, and 37.8% of the unburned plots.

Application example

To evaluate the effects of potential management actions, the model was used to compute the probability of wildfire occurrence in one stand located in central Portugal with an elevation of 235 m, slope of 35°, with 85 days of precipitation per year and assuming constant probability of ignition. A typical maritime pine stand in Portugal development starts with 2000 trees per ha and typically four thinning are performed. Each thinning is accompanied by a shrub cleaning. Thinnings with removal of shrubs decrease fire probability. The one-year fire probability ranged from 0% to 5% in a pure even-aged maritime pine stand (Fig. 3).

Discussion and conclusions

Some studies have addressed the characterization of wildfires in Portugal (Carreiras *et al.*, 2006; Marques *et al.*, 2011; Nunes *et al.*, 2005; Pereira and Santos 2003) focusing on variables that are either uncontrollable by forest managers (e.g. climate, topography) or that may mostly support strategic decision-making (e.g. to support strategic zoning and regeneration decisions). Yet forest management requires further information. Namely, wildfire risk models are needed that may help foresters design prescriptions to decrease the probability of wildfire occurrence.

Our study addressed Portuguese conditions and the need to include biometric variables that are readily available to forest managers to develop wildfire occurrence models. Logistic regression was used to develop the wildfire occurrence model for pure and even-aged Maritime pine stands in Portugal. Contrarily to González *et al.* (2006) it was not assumed that biometric variables did not change in the period extending from the inventory date to the wildfire occurrence date. This study further extended former studies by pioneering the introduction of shrub biomass in a wildfire occurrence model and by using ignitions points.

Previous studies used logistic methods to predict wind and snow damage probability as a function of stand variables (Jalkanen and Mattila, 2000; Lohmander and Helles, 1987) and also to predict fire ignition probabilities (Catry *et al.*, 2009; Vanconcelos *et al.*, 2001), showing to be an appropriate technique to model events which occurrence is a binomial outcome (Silva *et al.*, 2009; Monserud and Sterba, 1999).

A data set encompassing even aged maritime pine plots located in 61 wildfire perimeters was used to develop and test 4,109 models so that all relevant combinations of explanatory variables might be addressed. The model selection process preferred models with good ecological behavior over models with purely good statistical fit. The model selected showed good ecological behavior and good goodness-of-fit. All its explanatory variables were statistically significant and have a relationship with variables normally used to explain potential fire behavior. Validation of the models was done through studies of the performance of the functions. No specific validation data sets were set-aside and later used for that purpose. This was for two main reasons. First, the relatively small number of observations in the dataset. Second, the best possible parameter estimates were of greater interest. There are advantages and disadvantages of splitting the data set for model validation purposes as discussed by Kozak and Kozak (2003). They concluded that cross validation by data splitting and double cross validation may provide little information in the process of evaluating regression models.

Our results show that annual probability of wildfire occurrence increases with the shrub biomass load. Maritime pine is a normally planted for timber in pure stands. The lack of management of these areas, related to socio-economic constraints, may be the origin of these results. Some studies show that the fire occurrence probability and severity will increase as the shrub layer become more conspicuous, substantially dryer and more flammable due to higher temperatures (Castro *et al.*, 2003; Fernandes *et al.*, 2010; Schmidt *et al.*, 2002).

Wildfire occurrence is also impacted by quadratic mean diameter and number of trees. The probability of wildfire occurrence decreases with basal area. The indicator G/dg is negatively related to wildfire occurrence probability indicating that higher densities reduce fire probability. This is in line with other studies where, for example, tree size parameters (i.e. quadratic mean diameter) and density parameters (basal area) have also been used as an indicator of stand-level competition and have been shown to influence fire risk probability in forest stands in Catalonia (González *et al.*, 2006). Dense tree canopies in conifer stands reduce the exposure of surface fuels to wind and solar radiation and minimize understory vegetation development, hence decreasing surface fire intensity and fire probability (Fernandes *et al.*, 2010). The application of our risk model using a typical silviculture for maritime pine stands shows a slight increase in fire risk after thinning. This is in line with common knowledge as thinnings may result in an increase of dead surface fuels (slash) that increase the risk of forest fires (Carey and Shumann, 2003). Thinnings may also help decrease the moisture in the forest due to the increased surface wind speed and light availability as well as the increased growth of herbs and shrubs (Fernandes and Rigolot, 2007; Fernandes *et al.*, 2010; Jactel *et al.*, 2009).

According to the proposed model, wildfire risk increases with slope. This result is in concordance with findings from several studies (Carreiras and Pereira, 2006; González *et al.*, 2006; Pereira *et al.*, 2006; Rothermel and Philpot, 1983; Silva *et al.*, 2009) that indicate that slope facilitates the initiation of passive crown fires (torching) as increases likelihood of flame length attaining the tree crown. Pereira and Santos, (2003), developed a wildfire risk map for Portugal showing that areas with steeper slopes are more prone to burn. Often these fires are not controlled adequately. Climatic variables, and stand location variables were tested in the modeling process, but none of them were finally included since they did not improve the model. This was unexpected result, since previous research showed and influence of, for instance climatic conditions (González and Pukkala, 2007; Preisler *et al.*, 2004).

In the framework of forest management planning, this model may be used to predict the probability of a wildfire to occur if there is an ignition. Thus, it should be applied after using a wildfire ignition model such as the ones developed by Catry *et al.* (2008, 2009) or Vasconcelos, *et al.* (2001). Further these models may be integrated with a growth and yield model which predicts the stand development over time (Hanewinkel *et al.*, 2010). At each step of the growth simulation if an ignition occurs the simulator estimates the probability of wildfire occurrence. Then depending on the approach followed to integrate fire in forest management planning this probability may be transformed into a dichotomous variable (e.g. wildfire occurs or does not occur). This would be the case of using fire spread simulators (e.g. González-Olabarria and Pukkala, 2011) or stochastic simulation where the estimated probability would be compared to the cut-point (González-Olabarria *et al.*, 2008). However, if only information on the probability of wildfire occurrence is required, no cut-point would be used. This would fit for example to approaches presented by Pasalodos-Tato *et al.* (2010) and Garcia-Gonzalo *et al.* (2011).

If the approach followed needs to calculate whether a wildfire occurs or not over the planning horizon a cut-point must be defined and compared to each estimated probability (Hosmer and Lemeshow, 2000). In this study we would recommend to use a cut-value of 0.035. Although the false positives are higher than using smaller cut-values, this threshold allows correct prediction of the non-fire events in our dataset. This means that this model would overestimate the fire events but we consider that is most important to predict well these stands that most likely would not get burnt due to their structural conditions.

The knowledge that results from this study may be instrumental to understand the influence of certain variables on the probability of wildfire occurrence. It provided valuable information to integrate risk considerations in both operational and strategic management planning. This information may be used to decrease fire hazard by promoting less fire-prone stands. Reduced wildfire risk can be included as an objective in forest planning problems by means of targeting fuel loads and stocking levels. Developing plans that include risk reduction as an objective may help managers address fire prevention issues in forest planning.

It is important to acknowledge that whether a fire may or not occur in a stand does not depend solely on stand endogenous variables. It further depends on landscape composition and structure (Fernandes *et al.*, 2010; González *et al.*, 2006). A study from Reed (1994) shows that stands are often burned by wildfires that started in neighboring stands (the probability of a stand burning being increased by other stands burning). Further research may expand the current model to consider for example other climate (e.g. wind speed, maximum temperature in the fire season) or landscape structure variables (e.g. neighboring stands biometric variables). Yet the proposed model may help forest managers design prescriptions to manipulate stand endogenous variables that impact the probability of wildfire occurrence. In addition, fuel treatments (i.e. reduction of fuels in forests) may change wildfire behavior and enhance the effectiveness of fire suppression tactics (e.g. Mercer *et al.*, 2008).

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