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Developing Post-Fire *Eucalyptus globulus* Stand Damage and Tree Mortality Models for Enhanced Forest Planning in Portugal

Susete Marques, Jordi Garcia-Gonzalo, José G. Borges, Brigite Botequim, M. Manuela Oliveira, José Tomé and Margarida Tomé

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Forest and fire management planning activities are carried out mostly independently of each other. This paper discusses research aiming at the development of methods and tools that can be used for enhanced integration of forest and fire management planning activities. Specifically, fire damage models were developed for *Eucalyptus globulus* Labill stands in Portugal. Models are based on easily measurable forest characteristics so that forest managers may predict post-fire mortality based on forest structure. For this purpose, biometric data and fire-damage descriptors from 2005/2006 National Forest Inventory plots and other sample plots within 2006, 2007 and 2008 fire areas were used. A three-step modelling strategy based on logistic regression methods was used. In the first step, a model was developed to predict whether mortality occurs after a wildfire in a eucalypt stand. In the second step the degree of damage caused by wildfires in stands where mortality occurs is quantified (i.e. percentage of mortality). In the third step this mortality is distributed among trees. Data from over 85 plots and 1648 trees were used for modeling purposes. The damage models show that relative damage increases with stand basal area. Tree level mortality models indicate that trees with high diameters, in dominant positions and located in regular stands are less prone to die when a wildfire occurs.

Keywords forest fires, forest management, *Eucalyptus globulus* Labill, damage model, post-fire mortality
Addresses Technical University of Lisbon, School of Agriculture, Forest Research Center, Tapada da Ajuda, 1349-017 Lisboa, Portugal **E-mail** smarques@isa.utl.pt
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1 Introduction

Forest fire severity has increased substantially in the Mediterranean and in Portugal in the last decades (Alexandrian et al. 2000, Velez 2006, Pereira et al. 2006). In Portugal, since 1975 an average of 114 000 hectares per year have been burned by wildfires. The need to address fire risk in forest management planning is evident and yet forest and fire management planning activities are currently carried out mostly independently of each other. In order to include fire risk in forest management planning several issues need to be addressed. For example, it is important for foresters to know which trees are likely to survive after a wildfire. What variables are important predictors of tree mortality?

A variety of methods have been used to study post-fire mortality (e. g. Fowler and Sieg 2004). Most of them have been used to predict which trees will survive a fire after the event has occurred. Further, post-fire tree survival models have been mainly used to study the effects of prescribed burning on trees (Ryan and Reinhardt 1988) or to give guidelines to post-fire salvage logging operations (Rigolot 2004).

These methods may be classified into direct and indirect approaches. Indirect approaches for prediction of tree mortality are based on fire behavior parameters. They require the use of fire behavior simulators (e.g. Finney 1998, 2006). These simulators need information about weather conditions and fuel accumulation. Nevertheless this information is hard to predict over long planning periods (Rothermel 1991, Finney 1999, He and Mladenoff 1999, González et al. 2007). On the other hand, direct approaches to predict mortality are based on measurements of tree tissue damage. Direct approaches use two main categories of readily observable indicators to assess tree mortality (Ryan 1982). The first, crown damage, considers all damage to the tree canopy e. g. both without foliage ignition (crown scorch) and with foliage ignition (crown consumption). The second, bole damage assesses the impact of wildfires on the cambium. However, tissue damage is a variable that can hardly be predicted in management planning contexts.

If post-fire models are to be used in forest planning, they must provide information about the impact on mortality of variables whose future value can be estimated with reasonable accuracy. Further, these variables should be under the control of forest managers. Thus mortality models should include variables such as forest density, species composition or mean diameter. It has been shown that variables such as these are related with fire damage (Linder et al. 1998, Pollet and Omi 2002, McHugh and Kolb 2003). Managers may modify effectively expected levels of fire damage by targeting specific values for these variables (Pollet and Omi 2002, Agee and Skinner 2005, González et al. 2007). In this context, post-fire models may be used to develop alternatives that reduce expected losses due to fire.

Nevertheless, the development and/or use of a mortality model in forest planning has been limited to few studies (Reinhardt and Crookston 2003, González et al. 2007, Hyytiäinen and Haight 2009) and none of them related to Portuguese conditions. In this context, this study aims at developing post-fire mortality models for *Eucalyptus globulus* Labill that may be used for generating optimal management plans taking into account fire risk. In fact, albeit ecological diversity as a result of climatic influences that range from Mediterranean to Atlantic or continental, over 80% of the forest area is occupied by four species: Maritime pine (*Pinus pinaster*), eucalypt (*Eucalyptus globulus*), cork oak (*Quercus suber*) and holm oak (*Quercus rotundifolia*) (Marques et al. 2011). Eucalypts are exotic to Portugal, having been introduced to the country in 1830, mainly for ornamental purposes (Fontes et al. 2006). Currently, eucalypt is the most important pulpwood producing species in Portugal. Eucalypt plantations extend over 647 000 ha – about 20.6% of the total forest area in Portugal with a total yield of about 5.75 million m^3 per year (DGRF 2006). Eucalypt pulpwood is the key raw material of the pulp and paper industry.

Eucalypt is a highly flammable species. The bark catches fire easily. Deciduous bark streamers and lichen epiphytes tend to carry fire into the canopy and to disseminate it. Other features of eucalypt that promote fire spread include heavy litter fall, flammable oils in the foliage, and open crowns bearing pendulous branches, which encourages maximum updraft (Esser 1993). Nevertheless, despite the presence of volatile oils that produce a hot fire, leaves of eucalypt are classed as intermediate in their resistance to combustion, and juvenile leaves are highly resistant to flaming (Dickinson and Kirkpatrick 1985). However, eucalypt is seldom killed by fire (Esser 1993). Many authors have studied effects of fire on eucalypt; however, few studies have developed mortality models for eucalypt stands (Curtin 1966, Guinto et al. 1999).

The occurrence of stem death in a sample plot over a given period of time is a binomial outcome that may be modeled by logistic regression (Hosmer and Lemeshow 2000). These methods have been previously used to predict the probability of a single tree to survive or die due to different causes (Monserud and Sterba 1999, Guinto et al. 1999, McHugh and Kolb 2003, Rigolot 2004, Keyser et al. 2006, González et al. 2007). However, traditional modeling approaches generate mortality on all plots (Fridman and Ståhl 2001). Moreover, many studies predict the mortality rate without distributing mortality among trees in the stand.

When applying logistic models to predict mortality, both deterministic and stochastic approaches can be used (Monserud 1976, Monserud and Sterba 1999, Álvarez González et al. 2004). A deterministic method consists in the use of a threshold value within the interval 0–1; if the estimated probability of mortality exceeds the threshold value, the tree is assumed to die. A stochastic approach may encompass the drawing of a uniform random number in the interval 0–1; if the random number is lower than the estimated probability, the tree is assumed to die (González et al. 2007, Fridman and Ståhl 2001).

In this research, a three-step modeling strategy was used to develop the post-fire stand damage and tree mortality models (Woollons 1998, Fridman and Ståhl 2001, Álvarez González et al. 2004). Logistic regression methods were used in all three steps. In the first step, a model was developed to predict whether mortality occurs after a wildfire in a eucalypt stand. In the second step the degree of damage caused by wildfires in stands where mortality occurs is quantified (i.e. percentage of mortality). In the third step this mortality is distributed among trees. Data from over 85 plots and 1648 trees were used for modeling purposes. Models with good ecological behavior were preferred over models with purely good statistical fit.

2 Materials and Methods

2.1 Materials

The fire data used in this study consisted of wildfire areas of 2006 to 2008 in Portugal that were larger than 5 ha. Burned area mapping in 2006 to 2008 was obtained by automated classification of high-resolution remote sensing data (i.e., Landsat Multi-Spectral Scanner (MSS), Landsat Thematic Mapper (TM), and Landsat Enhanced TM+). In this period, about 125 thousand hectares burned in 3436 fire events. Data acquisition further encompassed the post-fire inventory of 85 plots in 2007 and 2008. 17 plots had been measured before the wildfire occurrence in the framework of the 2006 National Forest Inventory (NFI). These plots were identified by the overlay of NFI plots and fire areas using GIS tools (ArcGIS 9.2) (Fig. 1). In total, this analysis showed that 17 eucalypt plots out of the 12237 NFI plots were burned between 2006 and 2008. 68 additional burned plots in eucalyptus' stands were considered. These plots were measured in areas where the fire perimeter was known and trees had not been harvested. They were located all over the country and were inventoried (after the fire) at the same time as the burned NFI plots. The total 85 plots were located in 24 fires areas. In all these plots no trees had been harvested after the wildfire.

The post-fire inventory involved, in the case of all the 85 plots, both the measurement of biometric variables (e.g. height, diameter at breast height, burned stump height, burned canopy height, degree of stump destruction, fire damage) and the characterization of the plot (e.g. elevation, aspect, slope, presence of soil erosion, shrub species)(Table 1).

In the case of the 68 plots that had not been measured before the wildfire occurrence, reverse engineering was used to re-build the forest before the fire. In the case of plots with standing burned trees, pre-fire diameter dbh was assumed to be unaffected by fire. The equation developed by Soares and Tomé (2002), was used to estimate pre-fire height:

$$h = h_d \left(1 + \left(0.10694 + 0.02916 \frac{N}{100} - 0.00176 d_{max} \right) e^{0.0354 h_d} \right) \left(1 - e^{-1.81117 \frac{dbh}{h_d}} \right) \quad (1)$$

where h_d is the dominant height (m), N is the stand density (number of trees per hectare), d_{max} is the maximum tree diameter in the stand (cm) and dbh is the tree diameter at breast height (cm).

When at inventory date, the burned trees were broken or tissue was damaged making impossible to measure dbh, the stump diameters were measured and tree characteristics were obtained using reverse engineering (McClure 1968, Bylin 1982, Diéguez Aranda et al. 2003). For this purpose, an equation was adjusted using a 3966 eucalypt trees' dataset to predict the dbh for eucalyptus with R^2 of 0.9517:

$$\text{dbh} = -0.5207 + 0.82841 d_{stump} \quad (2)$$

where dbh is the tree diameter at breast height (cm) and d_{stump} is the stump diameter (cm). Once dbh was estimated, an equation developed for Eucalyptus (Tomé et al. 2007) was used to calculate the tree height:

$$h = \frac{\text{dbh}}{0.6733 + 0.0130\text{dbh}} \quad (3)$$

where dbh is the tree diameter at breast height (cm). Then, using dbh and tree height at the moment of inventory, the tree pre-fire height was estimated as before using Eq. 1.

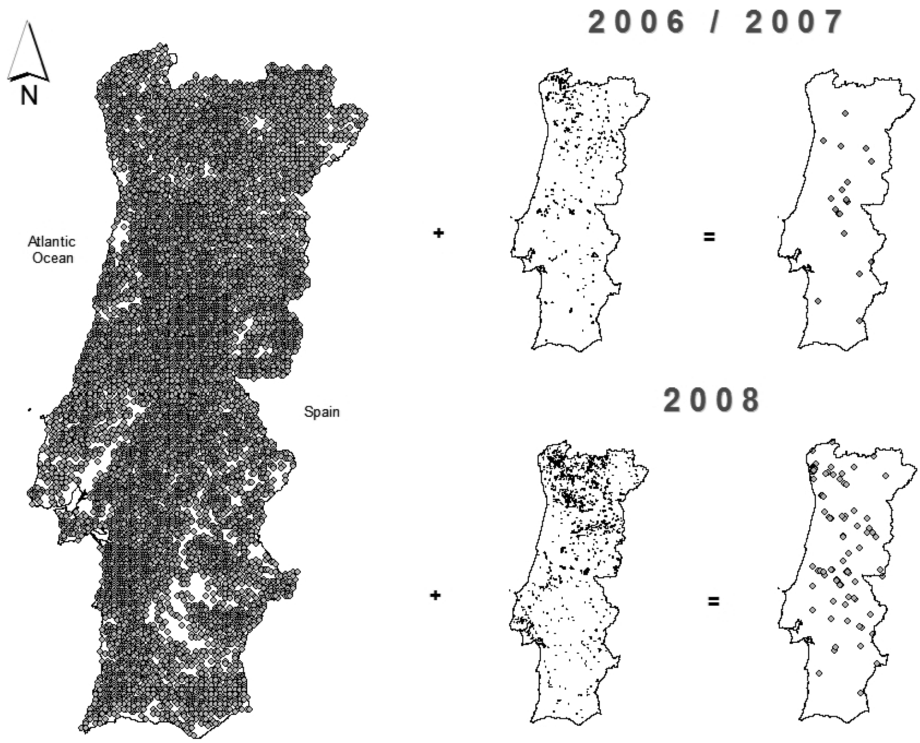

Fig. 1. Locating inventory plots for data acquisition. The map on the left shows the national forest inventory plots (≈12 200); the maps on top-right show the fire areas in 2006–2007 and the 43 burnt eucalypt plots; the maps on bottom-right, show the fire areas in 2008 and the 49 burnt eucalypt plots.

Table 1. Descriptive statistics for stand and tree level data. G is stand basal area (m^2 ha^{-1}); dg is the quadratic mean diameter (cm); N, number of trees; Pdead, proportion of dead trees in the stand; Sd standard deviation of tree diameters and Sh, standard deviation of tree heights of the stand; G/dg is non-linearly related to the number of trees per hectare. The predictor Sd/dg expresses the relative variability of tree diameters. dbh is de tree diameter at breast height (cm); g is the tree basal area (m^2 ha^{-1}); dbh/dg and g/G are competition indexes.

Variable	Stands without dead trees = 44				Stands with dead trees = 41			
	Max	Mean	Min	Sd	Max	Mean	Min	Sd
Altitude	491	186.05	0	140.48	644	212.96	0	126.41
Slope	32	13.12	0.60	8.67	27.80	12.63	0	6.54
Aspect	350	139.16	0	105.99	350	154.81	0	106.46
N	1811	574	20	444	1459	565	20	379
G	29.73	7.46	0.08	7.19	26.92	5.95	0.27	5.19
dg	36.51	12.78	7	5.38	26.00	12.18	4.79	4.54
Sd	10.76	3.06	0	2.30	12.30	3.72	0	2.22
Sh	5.14	2.05	0	1.34	7.06	2.90	0	1.94
G/dg	1.75	0.56	0.02	0.44	1.77	0.50	0.04	0.33
Sd/dg	0.45	0.24	0.01	0.12	0.81	0.34	0.01	0.20
Pdead	0	0	0	0	1	0.77	0.03	0.28
Variable	Alive trees = 877				Dead trees = 771			
	Max	Mean	Min	Sd	Max	Mean	Min	Sd
dbh	59.30	12.49	5.20	5.77	46.30	11.00	4.66	4.38
g	0.28	0.01	0.002	0.02	0.17	0.01	0.002	0.01
H	32.17	15.70	6.50	4.37	30.81	14.07	6.88	4.08
dg	3516.49	189.14	27.04	240.34	2143.69	140.13	21.69	140.68
BAL	1.03	0.22	0.00	0.23	1.34	0.29	0	0.29
dbh/dg	2.92	0.99	0.35	0.29	2.49	1.01	0.28	0.34
g/G	0.05	0.002	0.0001	0.004	0.05	0.00	0.0001	0.003

2.2 Methods

2.2.1 Modelling Mortality with Logistic Regression (General Approach)

The occurrence of stem death in a sample plot over a given period of time is a binomial outcome that may be modeled by logistic regression. Moreover, the logistic function is mathematically flexible, easy to use, and has a meaningful interpretation (Hosmer and Lemeshow 2000). The logistic model predicts a probability of an occurrence ranging continuously between 0 and 1. The dependent variable is dichotomous (e.g. death or no death). A cut-point may be defined and compared to each estimated probability (Hosmer and Lemeshow 2000) in order to assign '1' to the event of death and a '0' to the no death event. The logistic regression model may be presented as:

$$p = \frac{1}{1 + e^{-(\beta_0 + \beta_1 x_1 + \dots \beta_n x_n)}} \quad (4)$$

where the variable p is a measure of the total contribution of all the independent variables used in the model, x_1 to x_n are independent variables, β_0 is the intercept and β_1 to β_n, are estimated parameters or regression coefficients.

The logistic function was used to model stand-level damage and tree-mortality caused by wildfires. The Proc logistic procedure of SAS 9.1 (SAS Institute, Cary, NC) that estimates the parameters of the logistic equation with maximum likelihood method was used in all three steps of the proposed approach to develop the post-fire stand damage and tree mortality models. The information obtained from applying the stepwise variable selection method was combined with an understanding of the process of mortality.

2.2.2 Predicting Whether Mortality Will Occur in a Stand after a Wildfire

In order to predict whether mortality will occur in a stand after a wildfire, a stand-level binary variable was created. This variable takes the value '1' if death occurs and the value '0' if no death occurs in a stand. This modeling approach thus provides information to filter the stands where some mortality would occur out of the whole set of stands that also includes those where all the trees survive. A number of stand-level variables (e.g. plot characteristics, biometric variables (Table 1)) were used for estimating the probability of mortality occurrence. Model building considered both the ecological consistency of predictors (i.e. signs of coefficients that are biologically reasonable) and its statistical significance (i.e. 0.05 significance level and no systematic errors in the residuals).

2.2.3 Estimating Stand-Level Damage Caused by a Wildfire

In order to quantify mortality caused by wildfires in stands where mortality did occur, two stand-level variables were created. These variables indicated the number of trees that died as a consequence of a wildfire (i.e. number of events) and the total number of trees in the stand (i.e. number of trials). Then SAS Proc logistic procedure used these numbers to fit the logistic regression. The average proportion of dead trees in stands where mortality occurred as a consequence of wildfires was 40% in the case of eucalypt stands.

A number of stand-level variables related to topography (e.g. slope), biometric variables (e.g. mean diameter) and structure (e.g. standard deviation of tree heights) were used for estimating the probability of stand-level mortality caused by a wildfire (Table 1). All predictors had to be logical and significant at the 0.05 level without any systematic errors in the residuals.

2.2.4 Estimating Post-Fire Tree Mortality

We tried to find the best fitting and biologically reasonable model to describe the relationship between the response variable i.e. the tree status (alive or dead), and a set of explanatory variables (Table 1). For modeling purposes, a tree-level binary categorical variable was created. This variable takes the value '1' if death occurs, and a '0' if the tree survives.

As this is a two-stage model, a variable indicating the proportion of dead trees in the stand (Pdead) estimated with the stand level model (section 2.2.3) – was used to predict the post fire tree mortality. Therefore only trees present in stands where mortality was predicted were used to fit the tree mortality model. In total, 942 eucalypt trees were inventoried in burned plots, of which 771 were present in stands where mortality was predicted. Further predictors were selected by testing whether they improved the model. Selection considered the importance of the variable in terms of forest inventory and management as well as its simplicity, its ecological consistency and its statistical significance (i.e. 0.05 significance level and no systematic errors in the residuals). The "receiver operating characteristic (ROC)" curve was further used to test the model sensitivity. The ROC curve plots the probability of detecting true signal (sensitivity) and false signal (specificity) over all possible threshold values of the marker.

3 Results

The logistic model to predict whether mortality will occur in a eucalypt (Eq. 5) stand is:

$$\mathrm{Psd} = \frac{1}{1+e^{-(\beta_0+\beta_1 \frac{\mathrm{Sd}}{dg})}} \qquad (5)$$

where Psd is the probability of stand death to occur, Sd is the standard deviation of trees' diameters at breast height (cm), dg is the quadratic mean diameter (cm) of trees. The predictor Sd/dg expresses the relative variability of tree diameters.

The model indicates that higher values of Sd/dg (i.e. variability of tree diameters) increase the probability of death to occur in the stand (Eq. 5). All model coefficients were significant, at least at the 0.05% level as judged by the Wald χ^2 sta-

Table 2. Parameter estimates, standard errors (SE), Wald χ^2 statistics and p-values for the model predicting whether mortality will occur in a stand (Eq. 5).

Effect	Estimate	SE	Wald χ^2	$p > x^2$
β_0	–1.1742	0.4716	6.1994	0.0128
β_1	3.8942	1.4944	6.7906	0.0092

Table 3. Parameter estimates, standard errors (SE), Wald χ^2 statistics and p-values for the model predicting degree of damage caused by a wildfire (Eq. 6).

Effect	Estimate	SE	Wald χ^2	$p > x^2$
β_0	0.4654	0.0495	88.5417	<0.0001
β_1	0.00119	0.000133	88.4201	<0.0001
β_2	0.0214	0.00278	59.2655	<0.0001
β_3	0.00401	0.00520	59.3581	<0.0001
β_4	–0.1027	0.0103	100.3593	<0.0001

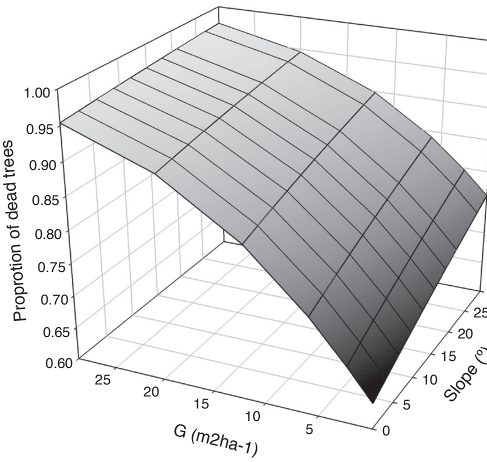

Fig. 2. Effect of stand basal area (G) and slope on the degree of damage in the stand, i.e. the proportion of dead trees (Eq. 6). The values were calculated with an altitude = 200 m and Sd = 3.47 cm.

tistic (Hosmer and Lemeshow 2000) (Table 2). The model was successful in predicting whether mortality did occur after the wildfire in 63% of eucalypt stands (i.e. percentage of concordant pairs).

The model to quantify mortality caused by wildfires in eucalypt (Eq. 6) stands where mortality did occur is:

$$\text{Pdead} = \frac{1}{1 + e^{-(\beta_0 + \beta_1 Alt + \beta_2 \text{Slope} + \beta_3 G + \beta_4 \text{Sd})}} \qquad (6)$$

where Pdead gives the proportion of dead trees in the stand, Alt is altitude (meters), Slope is measured in (°), *G* is the stand basal area ($m^2\,ha^{-1}$) and Sd is the standard deviation of the diameter of trees (cm).

All coefficients in Eq. 6 were significant, at least at the 0.05% level as judged by the Wald χ^2 statistic (Hosmer and Lemeshow 2000) (Table 3), while 65% of the data were successfully identified by the model as to whether death had or had not occurred for eucalypt. 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). This assessment showed no collinearity among variables included in the model.

The model indicates that the proportion of dead trees increases when stand basal area increases (Fig. 2). Moreover, steep slopes and higher altitudes contribute to increase this proportion (Eq. 6).

A tree-level mortality model predicting the probability of a tree to die due to a forest fire was developed:

$$\text{Ptm} = \frac{1}{1 + e^{-(\beta_0 + \beta_1 \text{dbh} + \beta_2 G + \beta_3 \text{Sh})}} \qquad (7)$$

where Ptm is the probability of a tree to die, dbh is the tree diameter at breast height (cm), *G* is the stand basal area ($m^2\,ha^{-1}$) and Sh is the standard deviation of the tree heights in the stand (cm). The higher the value of this variable the more irregular the stand is.

All coefficients in Eq. 7 were significant, at least at the $p < 0.05$ level (Table 4) as judged by the Wald χ^2 statistic (Hosmer and Lemeshow 2000). The model predicted the right outcome (death after the wildfire) in the case of 79.6 % of inventoried dead trees. The area under the ROC curve (0.798; Fig. 3) indicates excellent discrimination (Hosmer and Lemeshow 2000), thus showing that the selected model performs well.

Table 4. Parameter estimates, standard errors (SE), Wald χ^2 statistics and p-values for the tree-model predicting the probability of a tree to die due to a forest fire (Eq. 7).

Effect	Estimate	SE	Wald χ^2	$p>x^2$
β_0	3.6381	0.321	128.4757	<0.0001
β_1	–0.217	0.0251	74.8686	<0.0001
β_2	–0.1747	0.0312	31.4322	<0.0001
β_3	0.4311	0.0698	38.1911	<0.0001

The model (Eq. 7) indicates that trees with high diameters are less prone to die when a wildfire occurs (Fig. 4). Trees in stands with higher basal area have also lower mortality probability. Moreover, trees located in stands with higher variability in tree heights (Sh) are expected to have higher mortality probability (Fig. 5).

The odds ratio was further used to help interpret results as it provides an intuitive and easily understood way to capture the relationship between the independent and dependent variables. (Hosmer and Lemeshow 2000, Kleinbaum 1994). The odds ratio gives the increase or decrease in probability that a unit change in the independent variable has in the probability that the event of interest will occur. 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.

Results show that a 5 $m^2 ha^{-1}$ increase in stand basal area has an odd ratio of 0.418 which means that the probability of a tree to die would decrease by 58.2%. An increase in 5 cm in the dbh of the tree has an odd ratio of 0.338 which means that probability of death would decrease by 66.2%. The effect of an increase in one unit in height standard deviation would increase the probability in 53.9% (i.e. odd ratio of 1.539), which means that variability in tree sizes have a high impact on the probability of tree mortality.

Cut-point was calculated for the model predicting whether mortality will occur in a stand (Table 5). If the value that maximizes the correct classification rate (CCR = 63.5%) was used as

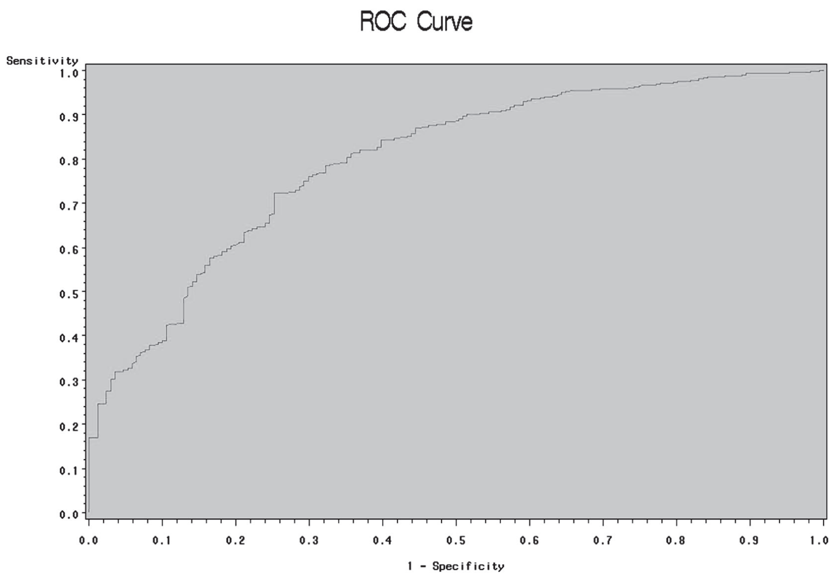

Fig. 3. ROC curve for Eucalypt tree-mortality model, showing an acceptable discrimination between tree mortality occurrence and non-occurrence (0.798) Models with ROC values 0.7 are considered to have an acceptable discrimination, ROC values 0.8 have excellent discrimination, and ROC values 0.9 are considered to have outstanding discrimination

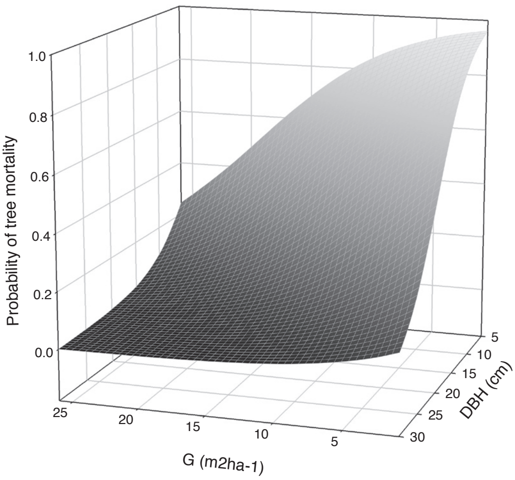

Fig. 4. Effect of tree-diameter (dbh) and basal area (G) on the probability of tree mortality using Eq. 7. The values were calculated using Sh = 2 which is the mean value in our dataset.

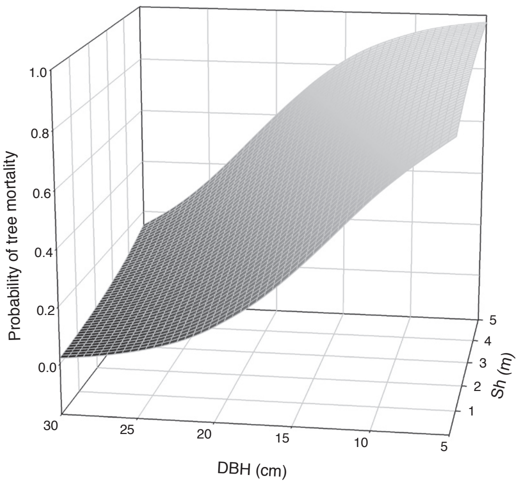

Fig. 5. Effect of tree-diameter (DBH) and standard deviation of the tree height (Sh) on the probability of tree mortality using Eq. 7. The values were calculated using G = 6 which is the mean value in our dataset.

Table 5. Prediction parameters depending on the cut-points used to transform a continuous probability into a 0–1 dichotomous value predicting whether there is mortality in a stand or not.

Cut point	CCR (%)	Sensitivity (%)	Speficifity (%)	False dead (%)	False alive (%)	Classified as dead (%)	Classified as alive (%)
0.41	52.9	75.6	31.8	49.2	41.7	72	28
0.42	58.8	73.2	45.5	44.4	35.5	64	36
0.43	58.8	70.7	47.7	44.2	36.4	61	39
0.44	55.3	63.4	47.7	46.9	41.7	58	42
0.45	52.9	53.7	52.3	48.8	45.2	51	49
0.46	55.3	51.2	59.1	46.2	43.5	46	54
0.47	52.9	46.3	59.1	48.6	45.8	44	56
0.48	51.8	43.9	59.1	50	46.9	42	58
0.49	52.9	43.9	61.4	48.6	46	41	59
0.5	57.6	43.9	70.5	41.9	42.6	36	64
0.51	56.5	36.6	75	42.3	44.1	31	69
0.52	57.6	36.6	77.3	40	43.3	29	71
0.59	58.8	26.8	88.6	31.3	43.5	19	81
0.6	60	26.8	90.9	26.7	42.9	18	82
0.61	58.8	24.4	90.9	28.6	43.7	16	84
0.62	58.8	24.4	90.9	28.6	43.7	16	84
0.63	60	24.4	93.2	23.1	43.1	15	85
0.64	61.2	24.4	95.5	16.7	42.5	14	86
0.65	62.4	24.4	97.7	9.1	41.9	13	87
0.66	63.5	24.4	100	0	41.3	12	88

CCR, Correct Classification Rate 63.5. The percentage of observed plots where tree mortality occurred was 48%. Sensitivity indicates the percentage of predictions where true signal was predicted correctly (i.e. stands with some mortality) and specificity refers to false signal (i.e. stands not showing mortality were correctly predicted).

criteria as suggested by Ryan (1997), the cut-point would be 0.66. According to this value, mortality would occur in 12% of the plots while mortality did actually occur only in 48%. This cut point did not show any false positive (i.e. stands that did not have any dead trees but were classified as if mortality had occurred) but 40% were false negatives (i.e. stands that had dead trees but where classified as if mortality had not occurred). Thus another criterion was tested to select the cut-point: the value where the sensitivity and the specificity curves cross. It provided a 0.45 cut-point value. Using this value led to a CCR of 59% and the percentage of stands classified as having mortality was 50%. If still another criteria was used e.g. the average observed percentage of event occurrence as suggested by Monseroud and Sterba (1999), the cut point value would be the same (i.e. 0.45). Using this cut-point, in 45% of the stands classified as not having mortality, some trees had actually died (i.e. false alive). If a cut point of 0.43 was chosen in 36% of the stands classified as not having mortality, some trees had actually died (i.e. false alive) and 70% of the stands showing mortality were well classified.

In the case of the individual tree mortality model, the cut-point value where the sensitivity and the specificity curves intersect was 0.83 (CCR of 73%). This would result in a sensitivity of 73% and specificity of 70%.

4 Discussion and Conclusions

A variety of methods have been used to study post-fire mortality (e. g. Fowler and Sieg 2004). Most of them have been used to predict which trees will survive a fire after the event has occurred. Further, post-fire tree survival models have been mainly used to study the effects of prescribed burning on trees (Ryan and Reinhardt 1988) or to provide guidelines to post-fire salvage logging operations (Rigolot 2004). Yet the use of these methods in forest management planning is constrained by its cost-effectiveness. Further, variables used to predict post-fire mortality (e.g. weather conditions, tissue damage) are seldom available.

Logistic regression has been used earlier for predicting tree-mortality as a consequence of prescribed fire (Botelho et al. 1996, Linder et al. 1998) and wildfire (Regelbrugge and Conard 1993, Harrington 1993, Stephens and Finney 2002, Beverly and Martell 2003, McHugh and Kolb 2003, Rigolot 2004, González et al. 2007). Yet, these models used variables that are seldom available for long-term forest planning. This explains why few studies have used post-fire mortality models in forest planning (Reinhardt and Crookston 2003, González et al. 2007, Hyytiäinen and Haight 2009). González et al. (2007) demonstrated the potential for the development and use of a damage model within a forest planning context. This model did not use tissue injury indicators or direct fire behavior parameters. Yet no management planning friendly damage models were available for Eucalypt stands in Portugal.

The proposed logistic modeling approach overcomes these obstacles and provides mortality models that may be readily used in stand or forest-level management planning e.g. mortality models that do not depend on direct descriptors of fire damage that are never available within a management planning framework. The proposed model rather provides information about the impact on mortality of variables whose future value may be estimated with reasonable accuracy. Further, these variables are under the control of forest manager (Pollet and Omi 2002, Agee and Skinner 2005, González et al. 2007). In this context, post-fire models may be used to develop alternatives that reduce expected losses due to fire. This model may be also used in post-fire mortality assessment when tree damage is no more visible or when trees have been cut in post fire salvage operations.

The advantage of the three-step methodology used in this study when compared to other traditional approaches is that it enables the identification of stands where no mortality occurs. Traditional models always generate some mortality for all plots (Fridman and Ståhl 2001). This research confirmed the potential of the proposed approach to develop mortality models that may be used in forest planning (Reinhardt and Crookston 2003, González et al. 2007, Hyytiäinen and Haight 2009).

The proposed approach used a large dataset encompassing 1858 trees in 92 plots located in 24 fire areas in Portugal. As fire areas are inventoried after each fire season by the Portuguese public administration, these 24 fire areas may result from more than one wildfire. Model fitting quality as assessed by concordance and area under the ROC curve suggests that the model has a good ability to discriminate post-fire mortality in eucalyptus stands in Portugal. In the framework of forest management planning, Eq. 5 may be used to predict whether mortality may occur in a stand after a wildfire. If mortality is predicted to occur, Eq. 6 may be used to estimate the degree of damage in the stand, i.e. the proportion of dead trees. Finally, the mortality at stand level may be then distributed among trees using Eq. 7. As these models are developed to support management planning, Eq. 6 may be used to estimate the number of trees that will die in the stand (i.e. percentage of trees), after a wildfire (if mortality indeed occurs). Equation 7 may then be used to predict the probability of mortality of each tree in the stand and to build a list of all trees in the stand ordered according to this probability (trees with higher probability of mortality are ranked first in the list). The management planning model may then select the trees that will be assumed to die for planning purposes by going down the list and stopping when it reaches the number of trees that are estimated to die (from Eq. 5). For this reason no threshold value is needed to transform the estimated probability into a dichotomous variable (e.g. death or no death). An illustrative example is given: assume Eq. 6 indicates that 50% of the trees in one stand will die if a wildfire occurs, assume we have 300 trees in the stand, then Eq. 7 would be used to calculate each tree probability to die and the 150 trees with higher probability to die will be selected and classified as dead for planning purposes. As suggested by González et al. (2007) the tree mortality equations can be used to generate mortality variation if a stochastic component corresponding to the residual variation of the stand level damage model is added to the prediction.

Prediction and classification do not follow the same pattern, so a compromise must be reached between good classification and good prediction of mortality when choosing a threshold level (cut-point) (Crecente-Campo et al. 2009). In our study, a cut-point of 0.43 for the model predicting whether mortality occur in a stand (Eq 5) seems appropriate. In the model predicting probability of a tree to die, a threshold value is not needed, however if a cut value of 0.83 is used, the sensitivity and specificity would be 73 and 71%, respectively.

Biometric variables selected for estimating post-fire mortality included the tree diameter (dbh), the relative variability of tree diameters (Sd/dg, Sd and Sh), and stand basal area (G). Other significant variables were related to fire behavior (i.e. slope) and stand location (i.e. altitude). In the stand-level damage model, steeper slopes increase the expected mortality. This is in concordance with other studies and may be explained by an easier transfer of heat uphill (Agee 1993, González et al. 2007, Hyytiäinen and Haight 2009). In our case, altitude correlates positively with the degree of mortality in burned areas. This is because most of the burned stands were located in high altitudes.

Eucalypt models indicate that in even-aged stands with higher tree diameters, fire damage is expected to be lower than in irregular stands with trees with smaller dimensions. This confirms results presented by Guinto et al. (1999) who found that eucalypts' resistance to fire was highly correlated with the thickness and the extent of protective bark tissue on the stem. These generally increase with the size of the individual. If bark is sufficiently thick eucalyptus trees may even survive also crown fires (Gill 1977). Moreover, the eucalypt mortality models also showed that in stands with larger trees, fire damage is expected to be lower. These results are in concordance with findings from other studies (Guinto et al. 1999, Pollet and Omi 2002, González et al. 2007). Extensive model testing led to the rejection of other biometric variables as predictors of stand-level damage after a wildfire.

At tree level, tree diameter (dbh) was found to be negatively related with tree mortality. In addition, trees located in stands with high tree height variability had higher probability of dying after a wildfire event. This is because irregular structures may facilitate crown fires. The combination of dbh and tree height variability indicates that dominant trees (e.g. trees with high diameters located in irregular stands) have lower probability of dying. This is in concordance with other studies (Ryan and Reinhardt 1988, Linder et al. 1998, González et al. 2007). This finding is also coherent with other studies (Monserud and Sterba 1999, Van Mantgem et al. 2003, González et al. 2005), dominant trees experiencing less competitive stress than smaller ones. The use of prescribed burning to reduce the potential wildfire intensity in European forests has been acknowledged by several authors (e.g. Vega et al. 1994, Mutch and Cook 1996). Moreover, when planning prescribed fire, sound prescriptions are required to constrain tree damage and mortality to acceptable levels (Botelho et al. 1996). Our results may help understand the effects of stand structure and tree-size on mortality and may thus help to define prescribed burns.

When no pre-fire inventory was available, reverse engineering was needed to reconstruct the stand. Thus the quality of the models is dependent on the quality of the equations used for that purpose. Further, this research considered mortality within a fixed period after the wildfire (i.e. each plot was measured only once one year after the wildfire event). In some cases, this may lead to an underestimation of mortality caused by the wildfire. Yet in doing so we avoided the situation where stands might have been harvested after the wildfire leading to a loss of data needed for the development of the model. Nevertheless, the development of the first post-fire mortality models in Portugal took into account all available data and information. No evaluation data were available, therefore model evaluation was made with the fitting data. It is never easy to select the best way to validate a model. The authors are aware of the advantages and disadvantages of splitting the data set for model validation purposes well discussed for instance in Kozak and Kozak (2003).

Fire damage models (e.g. Beverly and Martell 2003, González et al. 2007) are key to evaluate forest prescriptions and yet, again, no such models have been developed for eucalypt stands in Portugal. This research encompassed the development of post-fire *Eucalyptus globulus* stand damage and tree mortality models for enhanced forest planning in Portugal. They provide information about the impact of forest fires under alternative forest conditions.

These models are management-oriented; they provide information needed to quantify the effect of different management options on the expected fire damage thus further providing a more realistic estimation of future incomes. These models are instrumental to designing silvicultural strategies that may decrease the damage caused by wildfires. For example, developing silvicultural strategies at stand level aiming to maintain stands with lower densities and high tree diameters, performing earlier and heavier low thinnings may decrease post fire mortality.

The characteristics of the models provide opportunities for several applications e. g. integration of fire risk into forest management planning either at stand level (e.g. González et al. 2005a, 2007, 2008, Ferreira et al. Submitted) or at landscape level (González et al. 2005b). These models can easily be implemented in decision support systems that may allow the manager to minimize the expected losses due to wildfires when developing management plans.

The usefulness of post fire models in forest planning depends on the information they may provide about the impact on mortality of variables whose future value may be estimated with reasonable accuracy. Eucalypt post-fire stand damage and tree mortality models are based on variables that are under the control of forest managers (e.g. forest density, mean diameter). Thus we may further conclude that they can be used to integrate effectively fire risk into forest management planning.

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