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Instituto Superior de Agronomia
Universidade Técnica de Lisboa

INTEGRAÇÃO DA GESTÃO DO FOGO NA GESTÃO FLORESTAL

Caracterização da incidência de incêndios e modelação do dano

Susete Maria Gonçalves Marques

Dissertação para obtenção do Grau de Mestre em
Engenharia Florestal e dos Recursos Naturais

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Lisboa, 2009

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By the end of this stage, so important in my life, I want to devote thanks to all of those who made this possible for me.

First of all, I wish to thank Professor José Borges for all the support, patience and dedication to this project. I am also grateful for the encouragement he gave me, to carry out this task so important at this stage of a researcher life.

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For all …

THANK YOU!

Resumo

Os incêndios e especialmente os incêndios florestais nas últimas décadas tem vindo a aumentar tanto a sua área como o seu número sendo grandes causadores da destruição e perda de área florestal e de bens. Dado isto, foram desenvolvidos dois estudos, cujo contributo é fornecer instrumentos à integração da gestão do fogo na gestão florestal. O primeiro estudo, consiste na caracterização dos fogos em Portugal, e modelação da ocorrência de incêndio em três períodos em análise (1987-1991, 1990-1994 e 2000-2004). Foram obtidos três modelos matemáticos para a determinação da probabilidade de ocorrência de incêndio, perante determinadas características de ocupação de solo, topográficas e socioeconómicas. O segundo estudo, teve como objectivo a modelação do dano/perdas causadas pela passagem de incêndio em parcelas de povoamentos puros de *Eucaliptus globulus* Labill. Obtiveram-se três modelos de previsão da mortalidade e dano, sendo que o primeiro dará a informação se uma parcela terá ou não arvores mortas. O segundo modelo aplica-se às parcelas onde se preveja haver mortalidade e dar-nos-á a proporção de árvores mortas, numa parcela. O terceiro modelo, fornecerá informação sobre quais as árvores que efectivamente sofrerão morte devido ao incêndio.

Palavras chave: Incêndios, Modelação, Caracterização da incidência, Mortalidade, Dano

Abstract

The fires, especially forest fires in recent decades has been increasing both their area and number and are the cause of great destruction and loss of area and properties. Given this, two studies have been developed, whose contribution is to provide tools to integrate the management of fire in forest management. The first study is the characterization of fires in Portugal, and modeling the occurrence of fire in three periods under review (1987-1991, 1990-1994 and 2000-2004). We obtained three mathematical models for determining the likelihood of fire, before certain characteristics of land use patterns, topographical and socio-economic. The second study, aimed to the modeling of damage and losses caused by the passage of fire in plots of pure stands of *Eucalyptus globulus* Labill. This led to three models for the prediction of mortality and damage, and the first will give information if a plot will have not or dead trees. The second model is applied to the plots where there is expected mortality and give us the proportion of dead trees. The third model will provide information on the trees that actually suffer death due to fire.

Keywords: Fires, Modeling, Fire Incidence, Mortality, Damage

Resumo alargado

Os fogos são uma ameaça, para as populações, causando a destruição de propriedades rurais e urbanas, bem como a perda total ou parcial de área florestal. Dado que, o número de ocorrências de incêndio e áreas ardidas tem vindo a aumentar, nas últimas três décadas, torna-se urgente e de extrema importância, o desenvolvimento de políticas de prevenção contra incêndios. No entanto, a sua integração na gestão florestal, tem sido um desafio para os gestores, políticos e investigadores, em suma, para os decisores.

Para tal neste trabalho, foram desenvolvidos dois estudos que se prevêem ser ferramentas úteis na integração da gestão do fogo na gestão florestal, pois ajudam o decisor a prever a probabilidade de ocorrência de incêndio e no caso de ocorrência, o decisor tem a possibilidade de poder prever os danos e perdas que um incêndio possa causar em povoamentos florestais de puros de eucalipto.

O primeiro estudo, consiste na caracterização dos fogos em Portugal e modelação da ocorrência de incêndio em três períodos em análise (1987-1991, 1990-1994 e 2000-2004). Para a realização deste estudo, foram interceptados “shapefiles” contento informação de variáveis consideradas determinantes na ignição de fogos, sendo estas: topográficas, ocupação do solo e sócio-económicas. Através da modelação linear generalizada, “generalized linear models”, foram obtidos três modelos matemáticos que dão ao utilizador a probabilidade de ocorrência de incêndio, perante determinadas características.

O segundo estudo teve como objectivo a modelação do dano/perdas causadas pela passagem de incêndio em parcelas de povoamentos puros de *Eucaliptus globulus* Labill. Para o efeito foram realizados dois inventários florestais em parcelas cuja ocupação fosse de eucalipto, que arderam nos anos de 2006, 2007 e 2008 e que correspondem a parcelas medidas no IFN05-06. A realização destes inventários, teve por objectivo o registo de informações de dados biométricos e do estado vital das árvores e as condições em que se encontrava a parcela, após o incêndio. A recolha destes dados foi vital, para a modelação do dano, recorrendo ao método dos três passos (three step methodology). Este método consiste na obtenção de três modelos, sendo que o primeiro dará a informação se uma parcela com determinadas características terá ou não arvores mortas. O segundo modelo aplica-se apenas às parcelas onde se preveja haver árvores mortas e este dar-nos-á a intensidade de mortalidade, isto é a proporção de árvores mortas, numa parcela. O terceiro modelo, fornecerá informação sobre quais as árvores que efectivamente sofrerão morte devido ao incêndio.

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Terms List

AIC – Akaike Information Criterion

CLC – Corine Land Cover

DTM - Digital Terrain Model

GIS – Geographic Information System

IFN – Inventário Florestal Nacional

LOM – Land Ocupation Map

NFI – National Forest Inventory

ROC - Receiver Operating Characteristic

WGLM - Weighted generalized linear models

Introduction

This work contains two working papers, the first one deals with the characterization of fire incidence in mainland Portugal and the second talks about the assessment of damage on forest resources caused by fire in Eucalyptus stands.

These two studies were motivated due to the increase of fire incidence In the Mediterranean region, during the last three decades (Rego 1992, Moreno et al. 1998, Borges, 2006, Pereira et al., 2006; Velez 2006; Pausas, 2008). In Portugal, nearly 40% of the country's territory was burned in the period extending from 1975 to 2007. These wildfires had a substantial impact in the forested landscape configuration and composition in Portugal and they threaten people, destroy urban and rural property and damage forest resources (Borges .and Uva, 2006).

This context suggests the need for the development of effective fire prevention policies. It further places a challenge to forest researchers, policy-makers and managers as they call for methods and tools that may help integrate forest and fire management planning activities currently carried out mostly independently of each other (Borges, 2006). It's very important to develop scientifically sound methods that can be used by the public administration, non-industrial forest owners, industry and non-governmental organizations for enhanced integration of forest and fire management planning activities (Borges and Uva, 2006).

Several factors may explain the ignition and occurrence of forest fires, including the characteristics of the fuel (Rothermel 1972, Rothermel 1983, Albini 1976), other factors as weather, ignition sources, vegetation and topography (Agee 1993, Barton 1994 cited in Mermoz et al 2005, Viegas and Viegas 1994). The variables of the fuel load, distribution, and water content depends on the structure and vegetation composition, topography and climate that determine the mix available on site (Rothermel 1983). The topography directly influences fire behavior by increasing the heat transfer from the front of the fire to the fuel found in larger slopes (Rothermel 1983) and indirectly affect the spread through the type of fuel mixture present at the time prior to ignition of the fire (Kushler and Ripple 1997). Another variable factor of fire ignitions is the influence of human activity, and the risk of fire increases in the vicinity of urban areas. It is also in these areas that there is a greater ease in detecting and extinguishing fires (Pereira and Santos 2003). In addition to changes in landscape caused by a large-scale abandonment of rural areas is associated with an increased number of fires (Moreira et al. 2001).

The first study, presented in the first chapter of this thesis, obtained the data and thru statistical methods got models to explain the fire occurrence probability in forest cover types in Portugal, in three different periods (1987-1991, 1990-1994 and 2000-2004). There are several factors that explain the fire occurrence, and spread as fuel characteristics (Rothermel 1972, 1983; Albini 1976, Fernandes, 2001; Pereira and Santos 2003, Pereira et al 2006; Gonzalez 2007; Fernandes et al., 2005; Fernandes and Rigolot, 2007), topographic (Agee 1993; Viegas and Viegas 1994; Pereira, 2003, 2006, Carreiras and Pereira, 2006), socio-economic (Koutsias et al., 2002; Pereira and Santos, 2003; Mermoz et al., 2005; Carreiras and Pereira, 2006; Aranha and Gonçalo, 2001) and climate variables (Viegas and Viegas, 1994, Pereira et al., 2006, Gomes, 2008). This context highlights the need to characterize the current fire regime and understand the ecological and human drivers of observed patterns in areas burned.

The second study "Developing post-fire *Eucalyptus globulus* stand damage and tree mortality models for enhanced forest planning in Portugal" was developed to assess damage on eucalyptus stands caused by wildfires. Eucalypt is the third most important forest species in Portugal, extending over 647 x 10^3ha (20,6%) and yielding about 5.75 million m^3 of pulpwood per year (DGRF 2007). Fire constrains the economic viability of eucalypt commercial forestry (Nogueira 1990, Silva 1990, Moreira et al. 2001). In Portugal wildfires are the most severe threat to eucalypt plantations that provide key raw material for the pulp and paper industry. Over the last ten years they burned about 1.5 x10^5 hectares of eucalypt stands (NIR 2009).

In Portugal, some studies have focused on fire risk (Pereira and Santos 2003, Nunes et al. 2005, Carreiras et al. 2006. Some authors address the effects of wildfires on eucalypt plantations (Curtin 1966, Guinto et al. 1999). Nevertheless, no models of fire damage in eucalyptus plantation are available for our country. There are some studies on fire damage developed (Beverly and Martell 2003, Gonzaléz et al.2006) in some other countries. This lack of information to help address wildfire damage is a major obstacle to effective eucalypt forest management planning.

The mortality model after fire is related to damage observed after the passage of fire and want to model the probability of death of a certain tree. The possible damage that may result in the tree death, damage to the crown are the ones that are usually observed. Another type of widely used explanatory variable is the damage suffered at the bark. Of the variables used in modeling some may be obtained by allometric relationships, in particular, the thickness of the bark can be obtained depending on the species and diameter if there are models available for the tree. Some of the variables used are correlated with the intensity of the fire, as well as the type of fuel in the instant pre fire. The following is a list of variables used in modeling mortality at the level of the tree:

- Diameter (Beverly and Martell 2003; Botelho et al. 1998, Reinhardt et al. 1997; Wyant et al. 1986; Hely et al. 2003; Mutch and Parsons 1998; van Mantgem et al. 2003);
- Overall height (Beverly and Martell 2003, Reinhardt et al. 1997; Wyant et al. 1986; Hely et al. 2003);
- Percentage of damage to the canopy (Beverly and Martell 2003; Botelho et al. 1998, Reinhardt et al. 1997; Mutch and Parsons 1998; van Mantgem et al. 2003);
- Coarse Woody Debris (Beverly and Martell 2003);
- Bole Damage (Beverly and Martell 2003);
- Maximum heighht of stem blackening (Beverly and Martell 2003);
- Bark thickness (Reinhardt et al. 1997; Hely et al. 2003);
- Crown Scorch Height (Botelho et al. 1998, Reinhardt et al. 1997; Wyant et al. 1986; Hely et al. 2003);
- Length Crown Scorch (Botelho et al. 1998; Wyant et al. 1986);
- Crown Ratio (Reinhardt et al. 1997), length of the crown - Crown length (Wyant et al. 1986);
- Length Crown Consumption (Wyant et al. 1986);
- Maximum scorch height (Wyant et al. 1986);
- Crown base height (Hely et al. 2003);

Regarding the explanatory variables there is a wide range of variables that are related to the trees death as is illustrated by the previous list. Previous studies indicate consistently damage the crown, with the proportion of crown burned or killed, the most common indicator in predicting mortality after fire (Wyant et al. 1986, Saveland and Neuenschwander 1990, Stephens and Finney 2002, Wallin et al . 2003, McHugh and Kolb 2003, McHugh et al. 2003). The percentage of crown scorched or consumed is often characterized in terms of total canopy (Wyant et al. 1986, Saveland and Neuenschwander 1990, Stephens and Finney 2002, McHugh and Kolb 2003), but also estimated using the full length of the canopy (Harrington and Hawksworth 1990) or categorized in classes of damage (Harrington 1987, 1993, van Mantgem et al. 2003). Wyant et al. (1986) includes a measure of canopy consumed based on the height of the tree, and the inclusion of this variable in the adjustment increased the predictive ability of the model. The size of the trees is another variable that determines the modeling of mortality after the passage of fire. Larger diameters and taller trees are associated with increased ability to survive the loss (Wyant et al. 1986, Harrington 1993, Regelbrugge and Conard 1993, Stephens and Finney 2002, Thies et al. 2005, González et al. (2006)).The probability densities of death integrating the severity of the damage at the base of the tree is used in Regelbrugge and Conard (1993), McHugh and Kolb (2003), Ryan et al. (1988).

Regarding the association between the severity of the fire at ground level and mortality after fire can be found, for example Swezy and Agee (1991), McHugh and Kolb (2003). McHugh and Kolb (2003) categorize the severity according to a classification system used in Ryan (1982) and Ryan and Noste (1985) (no, low, moderate, or high). Stephens and Finney (2002) quantify the fuel in the soil before and after the passage of controlled burning. Analyzed the explanatory variables, there is another issue to keep in mind and that relates to the definition of death. The determination of objective criteria that can allow code to a particular dead tree.

Beverly and Martell (2003) developed one study where dead trees, without the presence of signs of the passage of fire are excluded from the analysis and are considered live trees with some green foliage, the species of the study is Pinus strobus L. The state of the crown is also used in Hely et al. (2003) to classify the tree as dead. An evergreen tree is considered dead if the canopy has green leaves, while in a coniferous tree is considered dead if the needles are missing or are all brown, or burned by fire. The latter criterion is used in van Mantgem et al. 2003. In Fernandes and Botelho (2004) suggested the value of 90% share of damage to the canopy in a Pinus pinaster , the tree is considered dead. For damage between 75% and 90%, the growth of the tree is severely damaged and is unlikely to cause death. In Weatherspoon and Skinner (1995) mortality is modeled at the stand. Classes are constructed from damage caused by fire. The response variable is the percentage of damage at the crown observable through aerial-photography, the explanatory variables are related to inventory data pre fire.

Logistic regression is used by several authors to calculate the probability of death at the tree (González et al. 2006; Beverly and Martell 2003, Hely et al. 2003, Stephens and Finney 2002; Kobziar et al. 2006; van Mantgem et al. 2003; Regelbrugge and Conard (1993)). Logistic regression is also used by Brown and DeByle (1987) and Ryan and Reinhardt (1988). Both references are cited in the manual FOFEM 4.0, see Reinhardt et al. (1997). The models use the thickness of the shell of the species into account the percentage of crown volume damaged, and differ in the minimum probability of death. González et al. (2006) developed two models for the tree level. The first uses predictors at the stand and tree variables and the second tree and observed proportion of dead trees. In terms of population the response variable is a transformation of the proportion of dead trees, the predictor variables involved topographic characteristics, composition and structure of the stand.

The main objective of this research was to develop a model that may be able to predict the effects of a wildfire in pure eucalyptus stands. Specifically, a model is developed that may assess wildfire mortality probability as a function of easily measurable biometric variables.

This work was written in article format, where each submitted articles is one chapter. These articles are structured following the journals indications and they were submitted to Annals of Forest Science (first study) and to Silva Fennica (second study). The author of this thesis, first author of the articles, and was the person who mainly develop the studies. The-authors of both articles, helped during the data treatment, statistic analysis and article redactions.

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Article I . Characterization of wildfires in Portugal

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I.1 -Abstract

Forest fires severity has increased in Portugal in the last decades. Climate change scenarios suggest the reinforcement of this severity. Forest ecosystem managers and policy-makers thus face the challenge of developing effective fire prevention policies. The characterization of forest fires is instrumental for meeting this challenge. An approach for characterizing fires in Portugal is presented. The proposed approach combined the use of geographical information systems and statistical analysis techniques. Emphasis was on the relationships between ecological and socioeconomic features and fire occurrence considering variations in land uses over time. Features maps were overlaid with perimeters of forest fires and the proportion of burned area was modeled using weighted generalized linear models (WGLM). This was instrumental to take into account the relative importance of the area associated with specific ecological and socioeconomic features when assessing its impact on the proportion of area burned. Results were discussed for three 5-years periods (1987–1991, 1990-1994 and 2000-2004). Descriptive statistics showed variations in the distribution of fire size over recent decades, with a significant increase in the number of very large fires. Modeling underlined the impact of the forest cover type on the proportion of area burned. The statistical analysis further showed that socioeconomic features such as the proximity to roads impact the probability of fires occurrence. Results suggest that this approach may provide insight needed to develop fire prevention policies.

Keywords: Fire characterization, fire risk, Geographic Information System, Land use.

I.2 - Introduction

The incidence of forest fires has increased in recent decades in the Mediterranean (Pereira et al., 2006; Velez 2006; Pausas, 2008). In Portugal, burned area reached a total of about 3.8×10^6 ha in the period from 1975 to 2007, i. e. equivalent to nearly 40% of the country area. Wildfires have a substantial economic, social, and environmental impact and became a public calamity and an ecological disaster affecting a considerable area in Portugal (Gomes, 2006). Forest managers and policy-makers thus face the challenge of developing effective fire prevention policies. This context highlights the need to characterize the current fire regime and understand the ecological and human drivers of observed patterns in areas burned.

Several factors may explain the ignition and spread of forest fires, such as fuel characteristics (Rothermel 1972; Rothermel 1983; Albini 1976), climate, ignition sources and topography (Agee 1993; Barton 1994; Viegas and Viegas 1994; Mermoz et al., 2005; Pereira, 2005). Fuel characteristics are a function of vegetation structure and composition in addition to anthropogenic factors. Topography, climate and socioeconomic factors determine the mix available at any given site (Rothermel 1983; Cardille et al., 2001; Lloret, 2002; Badia-Perpinya and Pallares-Barbera 2006). Topography further affects fire behavior, via its direct influence on flame geometry and, indirectly, through its effect on weather (Rothermel 1983; Kushla and Ripple 1997). Climate, cover type and topographical data are frequently used to develop fire risk indices (Pereira, 2005; Carreiras and Pereira, 2006). Recent characterizations of forest fires in Portugal underlined the impact of climate variables e. g. the number of days with extreme fire hazard weather on the number and size of fires (Viegas and Viegas, 1994, Pereira et al., 2005, Gomes, 2008). Pereira et al. (2006) further claimed that more than 2/3 of the inter-annual variation of the area burned can be explained by changes in weather conditions. Other studies have analyzed the impact of species composition and of fuel reduction activities on fire intensity and spread (Fernandes, 2001; Fernandes et al., 2005; Fernandes and Rigolot, 2007).

Yet another essential driver for ignition is the influence of human activity, which increases the risk of fire in the vicinity of road networks and urban areas (Aranha and Gonçalo, 2001; Koutsias et al., 2002; Pereira and Santos, 2003; Mermoz et al., 2005; Carreiras and Pereira, 2006). Nevertheless, due to human presence, it is easier to detect and suppress 73 fires in these areas (Pereira and Santos 2003). Traditional agricultural practices that encompass the use of fire (e.g. pasture renewal) may also lead to the occurrence of forest fires (Gomes, 2006). In Portugal, socioeconomic and demographic trends leading to large-scale abandonment of rural areas have contributed to increase fires' severity (Moreira et al., 2001).

The approach to wildfire characterization in Portugal discussed in this paper extended the scope of former studies by recognizing land uses changes over time, including socioeconomic variables and applying weighted generalized linear models rather than classical generalized linear models. It was instrumental for analyzing changes in burned area, number of fires, and fire distribution in Portugal and for examining the influence of topography, land use, socioeconomic and climate variables on fire occurrence probability. Specifically, it modeled the proportion of burned area to derive relationships between ecological and socioeconomic features and fire occurrence. The proposed approach combined the use of geographical information systems and statistical analysis techniques. Feature maps were overlaid with perimeters of forest fires and the proportion of burned area was modeled using weighted regression analysis. This study also extended the approach proposed by Gonzalez and Pukkala (2007) to further consider socioeconomic factors. Moreover, using a weighted rather than a classical generalized linear model to develop multiple regression analysis (Nelder and McCullagh 1989) was instrumental to take into account the relative importance of the area occupied by each land class.

I.3 - Data and Methods

Mainland Portugal (Fig. 1) extends over approximately 89000 km^2 located between 37°N and 42°N latitude and between 6°W and 10°W longitude. Altitude ranges from sea level to ca. 2000 meters, with the main elevations concentrated in central and northern Portugal. Mean annual temperature and precipitation follow a gradient of increasing temperature and decreasing rainfall from Northwest to Southeast. Mean annual temperature ranges from 7ºC to 18ºC, and annual rainfall from 400 mm to 2800 mm. Forestry is a key element in the Portuguese specialization pattern and forests and woodlands extend over one-third of the country. Further, shrublands extend over about 25% of the country's area (IFN 2006). 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*). The agricultural area extends over about 30% of the country's area (IFN 2006).

The descriptive analysis of wildfire occurrences in Portugal was based on historical fire information from a 33 year period (1975 to 2007). Burned area mapping was obtained every year in this period, 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+). Mapping by the the Remote Sensing Laboratory of Instituto Superior de Agronomia identified 35198 fire perimeters with burned areas equal or greater than 5 ha in the period 1975-2007.

In order to further analyze variations in the number and size of wildfires, this temporal horizon was classified according to the availability of land cover maps into three 5-year sub-periods (1987–1991, 1990-1994 and 2000-2004 (Moreira et al., in press)). The areas burned in each 5-year sub-period were included as map layers in the GIS database. This time frame was a compromise between having a larger sample size and minimizing the time impact on land cover changes.

Land cover type maps included 1990 and 2000 Corine Land Cover (CLC maps) produced by the Remote Sensing Group from Instituto Geográfico Português, at a scale of 1:100 000. The former (CLC 90) was produced using Landsat TM images from 1985 to 1987 while the latter (CLC 00) was produced using Landsat TM Images from 2000. In both cases, the standard classification encompassed 3 levels and 42 classes at the highest level. The CLC maps provided the information about cover type distribution in 1987 and 2000. The set of cover type maps used in this study further included a map (LOM90) produced by Instituto Geográfico Português using cartographic information at a scale of 1:25000 from aerial photography mostly dated from 1990. LOM90 land cover info was more detailed then CLC's and provided the information about cover type distribution in 1990.

In order to study the relationships between ecological and socioeconomic features and fire occurrence in the three sub-periods, cover types were classified into 10 classes (Tab. 1). This classification was based on land cover type information provided by the CLC and the LOM90 maps. For modeling purposes, four other environmental variables were considered: altitude, slope, proximity to roads, and population density (Tab. 1). The selection of variables and their ordinal-level segmentation was based on extensive preliminary data analysis.

Table I.1 – Description of Land use, Altitude, Slope, Proximity to roads, Population, N. days with precipitation greater than 1 mm and N. days with maximum temperature higher than 25ºC. The name of the categorical variable, as used in modeling, is given in parenthesis.

Variables	Class
Land cover	No fuel (Nofuel), Annual crop (AnnualCrop), Permanent crop (PermCrop), Agro-Forestry (Agro-For), Shrubs (Shrubs), Resinous or softwoods (Soft), Eucalyptus (Euc), Hardwoods (Hard), Softwoods mixed with Eucalyptus (SoftEuc), Hardwoods and Softwoods mixed with Eucalyptus, (HardSoftEuc)
Altitude (m)	< 200 (Alt<200), 200 – 400 (Alt200-400), 400 – 700 (Alt400-700), > 700 (Alt>700)
Slope (%)	0 – 5 (S0-5), 5-10 (S5-10), >10 (S>10)
Population (hab/km^2)	< 25 (Pop<25), 25 – 100 (Pop25-100), > 100 (Pop>100)
Roads proximity (m)	< 1000 (DistRd<1Km), > 1000 (DistRd>1Km)

The country's Digital Terrain Model (DTM) data were used to provide information about the distribution of altitude and slope. This DTM was obtained from elevation vector data used in the production of the Ortophoto-cartographic Series at a scale of 1:10 000 by the Instituto Geográfico Português. The distribution of the country's area per classes of altitude and slope considered a 225 meter grid size as the minimum fire patch area was 5 hectares. The Spatial Analysis module of ARCGIS 9.2 was used to get the altitude and the slope map layers. ARCGIS 9.2 was also used to create a 1 kilometer buffer around roads in the Estradas de Portugal, S.A. map and to get the GIS layer with the distribution of the study area per road proximity classes. The country population density data - number of habitants living in each parish – were obtained from Instituto Nacional de Estatística, (Population

Census from 1991 and 2001). These data were used to calculate population density per square kilometer and to get the population density class map. It was assumed that population density and road proximity did not change over the 5 years in each sub-period.

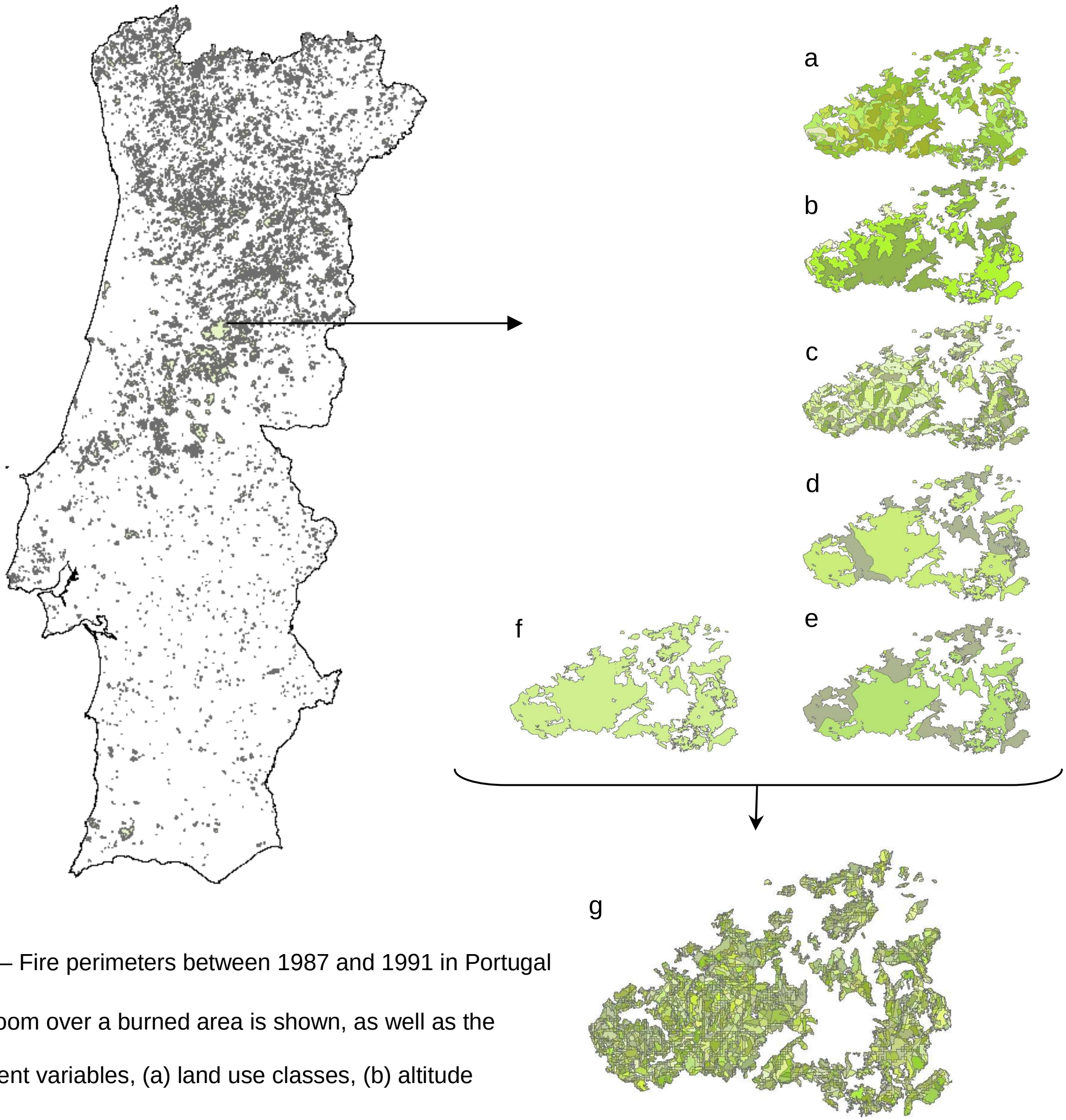


Figure I.1 – Fire perimeters between 1987 and 1991 in Portugal (left), A zoom over a burned area is shown, as well as the independent variables, (a) land use classes, (b) altitude classes, (c) slope classes, (d) roads proximity classes, (e) population density classes (f) perimeters of fire events, (g) layer indicating forest classes enclosed within the fire perimeters.

Land cover type, altitude, slope, proximity to roads and population density GIS layers for each of the 5-year sub-periods were overlaid using ARCGIS to produce three maps where each polygon represents a contiguous homogeneous area (thereafter designated as 163 stratum) (Fig.1). According to the 5 classification criteria used to determine the maximum number of homogeneous strata, 720 strata were observed. In the second sub-period (1990-1994), the cover type map was more detailed and 716 strata were present. 543 and 558 strata were present in the first (1987-1991) and third (2000-2004) sub-periods, respectively. The polygon coverage for each sub-period was overlaid with the burned area layer for the corresponding 5 year period. This provided the data needed to estimate the proportion of each stratum that was burned during the sub-period.

The relationships between ecological and socioeconomic features and fire occurrence in the three sub-periods were analyzed with weighted generalized linear models (WGLM). This approach takes as predicted variables transformations of the proportion of burned area in each stratum i (p_i) and as predictors the levels of the covariates (cover type, altitude, slope, proximity to roads and population density). The main objective of WGLM is to develop multiple regression analysis using the weighted least squares method (Nelder and McCullagh 1989), where the weights take into account the relative importance of the area of each stratum. This approach further contributes to meet multiple regression requirements. WGLMs are adequate for addressing situations where the variance is not constant, and/or when the errors are not normally distributed. This is often the case of response variables expressed as proportions (Nelder and McCullagh 1989). This study tested both *logit* and *arcsin* transformations of p_i :

$$y_i \equiv \log(\frac{p_i}{1-p_i}) = X_i^t\beta + \varepsilon_i \qquad (1)$$

$$\mu_i \equiv \arcsin(\sqrt{p_i}) = X_i^t\beta + \varepsilon_i \qquad (2)$$

Where the random errors e*I* may be considered independent Gaussian random variables with mean zero and variance $\varepsilon_i \sim N(0,\sigma^2)$, $i = 1,\ldots,n$ β is the regression coefficient vector associated with the covariate vector X_i .

The models were estimated using the backward logistic regression and the 191 parameters where estimated using the method of maximum likelihood in the R software version 2.7 (R Development Core Team 2008). This estimation considered all the covariates and the relevant interactions between covariates.

Both the coefficient of determination, pseudo R^2, and the Akaike Information Criterion (AIC) were used to select the best model for each 5-years sub-period. After this selection, the goodness of fit of each model was tested using deviation statistics. The size of the discrepancy between the fitted values produced by the model and the values of the data is a measure of the inadequacy of the model. Deviation statistics measure the discrepancy in a WGLM in order to assess goodness of fit. If L denotes the likelihood and D the deviance of a model involving p parameters, the deviance may be simply defined as minus twice the log likelihood D=-2log L. These statistics have a Chi-square distribution and were compared to p-values to test the hypothesis of model adequacy. To further assess the goodness of fit, model residuals were analyzed using Normal Q-Q plots and Cook's distances. Finally, a collinearity diagnostics was conducted to check if the covariates were correlated.

I.4 - Results

In the 33 years' period (1975 to 2007), there were 35194 wildfires extending each over an area greater than 5 ha. They burned about 3.8 x 10^6 ha. The analysis of yearly data (Fig. 2) shows that the burned area ranged from 15500 ha in 1977 to 440000 ha in 2003. In the year with the largest burned area (2003) a single fire perimeter extended over about 58000 ha.

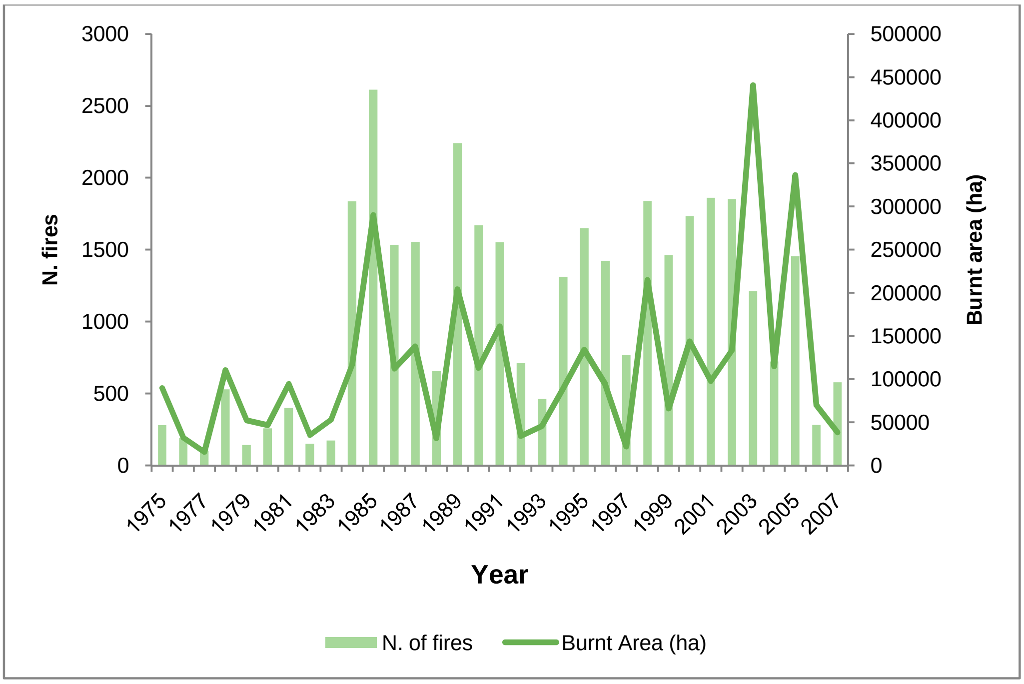


Figure I.2– Annual burned area and number of fires recorded in Portugal during the period 1975-2007

In the first sub-period (1987-1991), there were 7672 wildfires and the total burned area extended over 647312 ha. Only 232 wildfire perimeters were larger than 500 ha, accounting for 43% of the total area burned in the sub-period (Tab. 2). In 1987, there was a large wildfire that burned nearly 13000 ha. In 1988, only 656 wildfires were recorded burning about 4% of the total burned area for in this sub-period. The severity of wildfires was higher in 1989. In this year the burned area and the number of fires accounted for about 32 and 30% of the burned area and the number of fires in this sub-period, respectively.

Table I.2 – Number of fire events and total area burned, during the sub-periods 1987-1991, 1990-1994 and 2000-2004. In parenthesis the percentage.

Fire size class (ha)	Period 1		Period 2		Period 3	
	N. fires	**Burned area**	**N. fires**	**Burned area**	**N. fires**	**Burned area**
[5, 50[	5608 (73,1%)	104120,09 (16,08%)	3020 (74.83%)	56293,35 (17.08%)	5481 (74.24%)	94151,29 (10.12%)
[50, 250[	1559 (20,32%)	171509,98 (26,50%)	771 (19.1%)	80203,65 (24.33%)	1406 (19.04%)	151325,42 (16.26%)
[250, 500[	273 (3,56%)	95684,55 (17.78%)	132 (3.27%)	45642,41 (13.84%)	232 (3.14%)	80796,71 (8.69%)
[500, 1000[	149 (1,94%)	103694,94 (16.02%)	68 (1.68%)	45670,89 (13.85%)	137 (1.86%)	94864,80 (10.2%)
[1000, 2500[	66 (0,86%)	96176,30 (14.86%)	32 (0.79%)	44772,09 (13.58%)	88 (1.19%)	133315,85 (14.33%)
[2500, 5000[	13 (0,17%)	44654,79 (6.9%)	9 (0.22%)	32766,65 (9.94%)	19 (0.26%)	64736,02 (6.96%)
[5000, 10000[	3 (0,04%)	18706,20 (2.89%)	4 (0.1%)	24328,62 (7.38%)	10 (0.14%)	76247,41 (8.20%)
[10000, 20000[	1 (0,01%)	12765,96 (1.97%)	0 (0.00%)	0,00 (0.00%)	6 (0.08%)	91432,75 (9.83%)
>= 20000	0 (0,00%)	0,00 (0.00%)	0 (0.00%)	0,00 (0.00%)	4 (0.05%)	143257,52 (15.4%)
Total	**7672**	**647312,81**	**4036**	**329677,66**	**7383**	**930127,77**

In the second sub-period (1990-1994), there was a lower number of wildfires (5706) and the total burned area extended over 442745 ha. The average area burned per wildfire (77 ha) was also the lowest among all three sub-periods. In this sub-period, 149 wildfires extended over 500 ha, accounting for 44% of the burned area (Tab. 2). Yet none extended over 10000 ha. In 1993 only 462 wildfire events were recorded, the lowest yearly number in the sub-period.

During the third sub-period (2000-2004), both the number of wildfires (7383) and the total burned area (930128 ha) increased substantially. In this sub-period, only 264 wildfires extended over 500 ha and yet they accounted for 65% of the burned area (Tab. 2). Moreover, four wildfire perimeters extended over an area greater than 20000 ha. They occurred in 2003 and 2004 and they represented 15% of the burned area in the third sub-period. Further, the area burned in 2003 accounted for about 47% of the area burned in this 5-years sub-period.

Descriptive statistics of wildfires historical data provided information about changes in the number and in the size of wildfires during the three study periods (Tab. 3)

Table I.3 - Descriptive statistics of wildfires historical data for the periods (1987-1991, 1990-1994 nd 2000-2004)

Period	Year	Burnt Area (ha)	N. of fires	Medium Burnt Area (ha)	Maximum Burnt Area (ha)	Minimum Burnt Area (ha)
1	1987	137781.6325	1553	88.71966036	12765.96	5.04
	1988	31325.65895	656	47.75252888	729.6086119	5.04
	1989	204044.39	2242	91.00998663	2565.806486	5.020254338
1 and 2	1990	113067.9595	1670	67.70536495	7716.80259	5.010773496
	1991	161093.1724	1551	103.8640699	5983.578285	5.025300674
2	1992	34219.67583	712	48.06134246	6541.370575	5.007035363
	1993	45447.51849	462	98.37125215	6797.852231	5.04617219
	1994	88917.29401	1311	67.82402289	1191.073015	5.03070323
3	2000	143885.9496	1734	82.97920971	3840.847952	5.028395318
	2001	97666.18505	1861	52.48048632	8652.425584	5.01159916
	2002	133204.105	1853	71.88564761	4949.931696	5.006865492
	2003	440396.7875	1212	363.363686	58012.75648	5.011536296
	2004	114974.7469	723	159.0245462	23219.26154	5.13

Yet this information had to be combined with other spatial variables such as topography, land cover, proximity to roads and population density to help explain those changes and to identify fire occurrence patterns at the landscape level e.g. to identify the areas that are most susceptible to fire. The ten most burned combinations, in the three periods show that shrubs is the most vulnerable forest cover (Tab. 4).

Table I.4 – The ten most burned combinations, in the three periods.

Period 1987-1991	Period 1990-1994	Period 2000-2004
Shrubs,Alt>700,S>10,DistRd>1Km,Pop<25	Shrubs,Alt>700,S0-5,DistRd>1Km,Pop<25	Hard,Alt200-400,S0-5,DistRd>1Km,Pop<25
Shrubs,Alt>700,S0-5,DistRd>1Km,Pop<25	Shrubs,Alt400-700 ,S5-10,DistRd>1Km,Pop<25	Shrubs,Alt>700,S0-5,DistRd>1Km,Pop<25
Shrubs,Alt>700,S5-10,DistRd>1Km,Pop<25	Shrubs,Alt>700,S5-10,DistRd>1Km,Pop<25	Shrubs,Alt400-700 ,S5-10,DistRd>1Km,Pop<25
Shrubs,Alt400-700 ,S5-10,DistRd>1Km,Pop<25	Shrubs,Alt400-700 ,S>10,DistRd>1Km,Pop<25	Shrubs,Alt>700,S5-10,DistRd>1Km,Pop<25
Shrubs,Alt>700,S>10,DistRd>1Km,Pop25-100	Shrubs,Alt>700,S>10,DistRd>1Km,Pop<25	Shrubs,Alt>700,S>10,DistRd>1Km,Pop<25
Shrubs,Alt400-700 ,S>10,DistRd>1Km,Pop<25	Shrubs,Alt400-700 ,S5-10,DistRd>1Km,Pop25-100	Hard,Alt<200,S0-5,DistRd>1Km,Pop<25
Shrubs,Alt400-700 ,S5-10,DistRd>1Km,Pop25-100	Shrubs,Alt>700,S>10,DistRd>1Km,Pop25-100	Shrubs,Alt200-400,S0-5,DistRd>1Km,Pop<25
Shrubs,Alt400-700 ,S>10,DistRd>1Km,Pop25-100	Shrubs,Alt400-700 ,S0-5,DistRd>1Km,Pop<25	Shrubs,Alt400-700 ,S0-5,DistRd>1Km,Pop<25
Shrubs,Alt400-700 ,S0-5,DistRd>1Km,Pop<25	Shrubs,Alt>700,S5-10,DistRd>1Km,Pop25-100	Shrubs,Alt400-700 ,S>10,DistRd>1Km,Pop<25
Shrubs,Alt>700,S5-10,DistRd>1Km,Pop25-100	Shrubs,Alt400-700 ,S>10,DistRd>1Km,Pop25-100	AnnualCrop,Alt200-400,S0-5,DistRd>1Km,Pop<25

In both the first (1987-1991) and the second (1990-1994) sub-periods, the highest percentage of burned area occurred in the stratum with shrubs at altitudes over 400 meters, located at more than a kilometer from roads and with population density lower than 25 habitants per km2. In the third sub-period (2000-2004), the stratum with the highest percentage of area burned was hardwoods, at altitudes between 200 and 400 meters in areas with low population density and more than a kilometer from a road. This stratum totaled approximately 28500 ha. In the case of other strata, the relative importance of the percentage of area burned was approximately the same in all three sub-periods.

Models using the logit transformation performed better than arcsin transformation and were further used in this study. The coefficients of determination (R^2) of the weighted generalized linear models (WGLM) for the three sub-periods reached values between 0.87 and 0.89 in the case of the *logit* transformation of $p\ i$ (Tab. 5).

Table I.5 – Models for predicting proportion of area burned for periods 1987-1991, 1990-1994 and 2000-2004. The predicted variable (y) is the logit transformation of the proportion of burned area (p).

Parameter	Period 1 (1987 -1991)				Period 2 (1990-1994)				Period 3 (2000-2004)			
	Estimate	S E	t value	P value	Estimate	S E	t value	P value	Estimate	S E	t value	P value
β_0	-4,801	0,144	-33,513	< 2e-16	-4,66	0,123	-37,760	< 2e-16	-3,662	0,125	-29,263	< 2e-16
β_1 Cover type												
AnnualCrop	0,564	0,108	5,230	2,45e-07	-0,505	0,092	5,493	5,55e-08	0,388	0,094	4,108	4,61e-05
Euc					1,06	0,125	8,477	< 2e-16				
Hard	1,511	0,119	12,730	< 2e-16	0,09	0,1	- 0,899	0,369	1,587	0,103	15,485	< 2e-16
HardSoftEuc	2,439	0,143	17,074	< 2e-16	0,668	0,136	4,895	1,22e-06	1,597	0,127	12,599	< 2e-16
NoFuel	-1,045	0,176	-5,950	4,90e-09	-0,964	0,13	-7,430	3,17e-13	-1,687	0,141	-11,932	< 2e-16
PermCrop	-0,343	0,139	-2,460	0,01423	-0,688	0,11	-6,319	4,69e-10	0,159	0,124	1,322	0,187
Shrubs	2,858	0,12	23,777	< 2e-16	1,823	0,1	18,451	< 2e-16	2,159	0,103	20,955	< 2e-16
Soft	2,308	0,133	17,409	< 2e-16	1,478	0,107	13,934	< 2e-16	1,793	0,119	15,102	< 2e-16
SoftEuc					1,484	0,155	9,547	< 2e-16				
β_2 Altitude												
Alt>700	1,112	0,091	12,233	< 2e-16	1,38	0,079	17,441	< 2e-16	0,553	0,079	6,994	7,89e-12
Alt200-400	0,536	0,062	8,639	< 2e-16	0,468	0,054	8,709	< 2e-16	0,553	0,053	10,368	< 2e-16
Alt400-700	0,906	0,08	11,588	< 2e-16	1,158	0,067	17,241	< 2e-16	0,525	0,067	7,824	2,69e-14
β_3 Slope												
S0-5	-0,933	0,09	-10,426	< 2e-16	-0,617	0,078	- 7,883	1,23e-14	-0,542	0,078	-6,968	9,38e-12
S5-10	-0,301	0,096	-3,130	0,00185	0,008	0,084	0,099	0,921	-0,011	0,083	-0,133	0,894
β_4DistRoads												
DistRd>1Km	0,228	0,053	4,842	1,69e-06	0,252	0,046	5,471	6,24e-08	0,293	0,04	6,422	2,94e-10
β_5Population												
Pop>100	-0,312	0,076	-4,099	4,80e-05	-0,308	0,066	-4,651	3,95e-06	-0,908	0,065	-13,913	< 2e-16
Pop25-100	0,386	0,059	6,554	1,33e-10	0,57	0,051	11,205	< 2e-16	-0,23	0,051	-4,477	9,23e-06
R^2	0,89				0,87				0,88			
AIC	1,762				2,182				1,681			

The estimation of the model consideration of all covariates and possible interactions, however, interactions were not significant and where not included in the final models. The statistics suggest that the model may be used effectively to explain wildfire incidence (Tab. 4). The goodness of fit by the three models was tested using deviance statistics. The values were 0.316, 0.317 and 0.242, in the case of the first, second and third sub-periods, respectively. The comparison between these deviance statistics and the corresponding p-values (1 in all three sub-periods) for Chi-square distributions with 523, 698 and 542 degrees of freedom leads to the acceptance of the null hypothesis that the models fit well the data in all three sub-periods. The adequacy of the model was further checked by the analysis of the residuals by using both Normal Q-Q plots and Cook's distances (figure 3). This analysis further confirmed the goodness of fit by the three models. The former showed that residuals are normally distributed while the latter showed that there are no large residuals that may distort the 269 accuracy of the regression (all distances are lower than .05).

The computation of values of the generalized variation inflation factors (GVIF) was instrumental for the collinearity diagnostic. GVIF values showed that the covariates were not correlated and that multicollinearity was not a problem as they ranged from 1.001 to 1.01, approximately (Tab. 6).

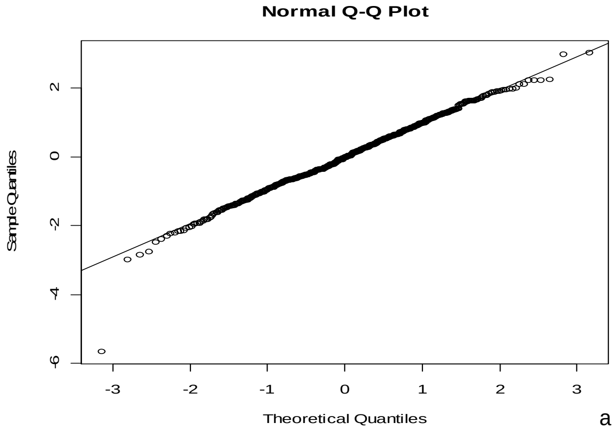
Table I.6 – Values of the generalized variation inflation factors (GVIF) for the collinearity diagnostics for models for periods 1987-1991, 1990-1994 and 2000-2004.

	Period 1987-1991		**Period 1990-1994**		**Period 2000-2004**	
	GVIF	**Df**	**GVIF**	**Df**	**GVIF**	**Df**
Land Cover	1.008976	8	1.006712	9	1.013297	8
Altitude (m)	1.005626	3	1.003827	3	1.005385	3
Slope (%)	1.004289	2	1.00193	2	1.002738	2
Roads Proximity (m)	1.000877	1	1.001812	1	1.001909	1
Population (hab/Km^2)	1.002007	2	1.005433	2	1.010138	2

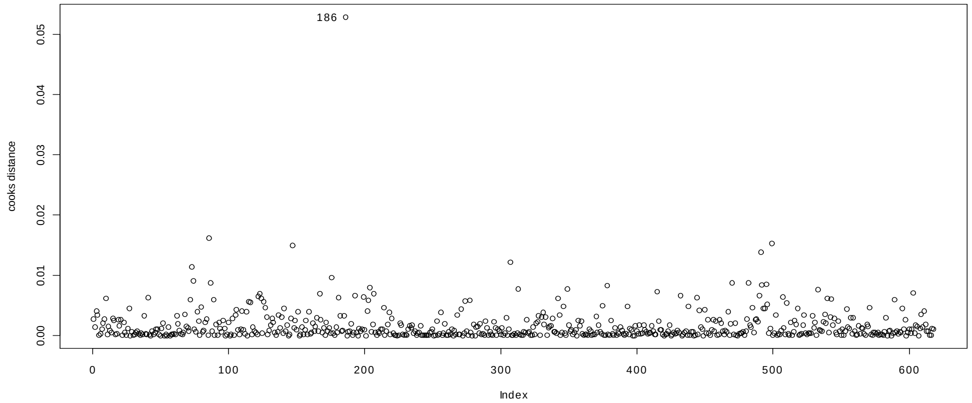
The weighted generalized linear models (WGLM) confirmed that in the first sub-period, areas occupied by shrubs were more likely to burn. Mixed stands (HardSoftEuc), Softwoods and Hardwoods were the second, third and fourth cover types that most impacted the proportion of area burned.

As expected, the no fuel (NoFuel) and the permanent crops (PermCrops) land cover classes had a negative impact on the proportion of burned area. In the case of this sub period, the land cover type map CLC 90 does not provide data about individual forest species and the Euc and SoftEuc classes are not possible to be analyzed separately (i.e. both eucalyptus and hardwoods are pooled in the same category). As for altitude, the regression coefficients indicate that higher altitude values were associated with a higher proportion of burned area. The proximity to roads' covariate had a similar behavior, e.g. larger distances lead to an increase of the proportion of area burned. Conversely, the increase of population density lead to a decrease of the proportion of area burned.

Period 1987-1991

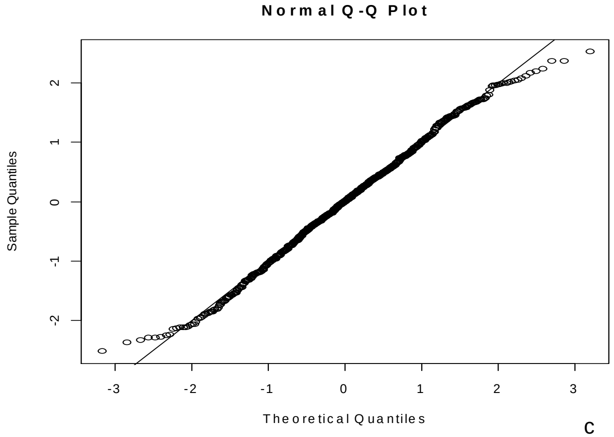


a

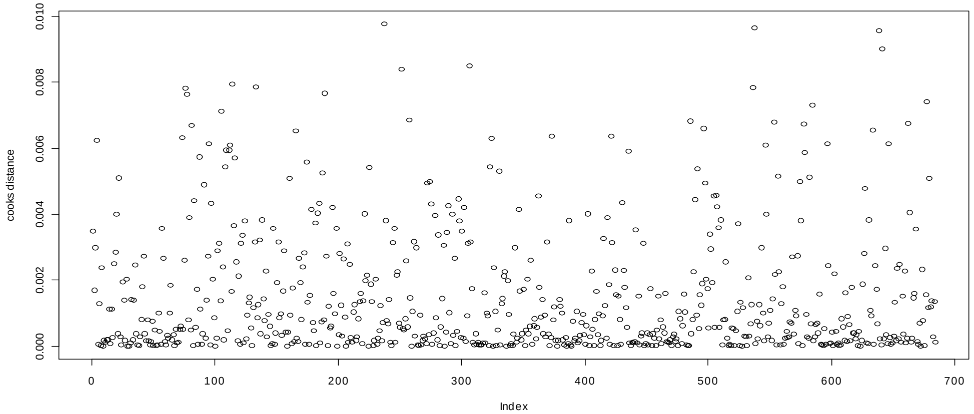


b

Period 1990-1994



c



d

Period 2000-2004

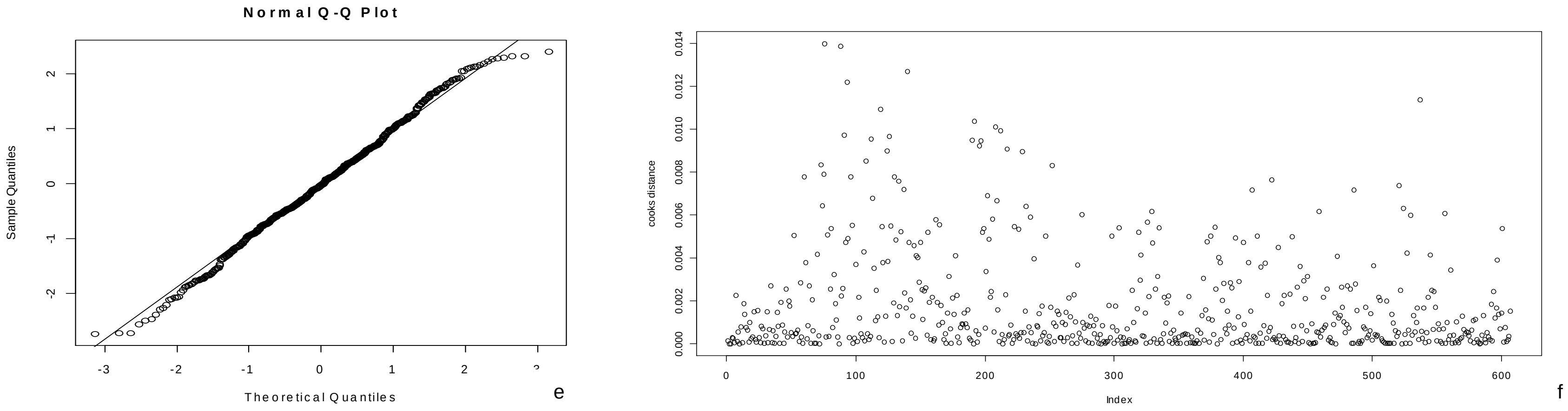


Figure I-3 – Normal Q-Q plots (a, c and e) and Cooks Distance (b, d and f) for the three periods 1987-1991, 1990-1994 and 2000-2004

The model developed for the third sub-period showed similar patterns than the one for the first period. It showed that areas occupied by shrubs were more likely to burn. Regarding the proximity to roads, the regression coefficients indicate that larger distances lead to an increase of the proportion of area burned whereas the increase of population density lead to a decrease of the proportion of area burned.

Compared to the other two sub-periods, the model developed for the second sub-period included a more detailed description of land cover categories with a separation of different forest types (e.g. Euc and SoftEuc). In this sub-period, the shrublands were still the class that most impacted the proportion of area burned i.e. they increase the proportion of area burned. Furthermore, the areas occupied by conifers and eucalyptus are also very susceptible, whereas mixed forests including hardwoods were less affected by fire. On the contrary, the no fuel, annual and permanents crops land cover classes had negative impact on the proportion of burned area. In this period, areas with slopes greater than 5% were more susceptible to burn. In general, the higher the altitudes and distance to roads (accessibility), the higher the proportion of area burned. As in the other periods, the increase of population density lead to a decrease of the proportion of area burned (Table 4).

I.5 - Discussion and conclusions

An approach for characterizing fires in Portugal is presented. The analysis of historical fire data allowed modeling the variation in the distribution of fire size, changes in burned area and number of fires over the study period. The combination of wildfire historical data with ecological and socio- economic variables (namely topography, land use, proximity to roads and population density) helped explain changes in number and size of wildfires. It further contributed to identify fire occurrence patterns at the landscape level. The results may help managers and policy makers to develop effective fire prevention policies.

A novelty of the proposed approach is the use of weighted generalized linear techniques (WGLM). The use of WGLM rather than classical generalized linear models allows taking into account the relative importance of the area associated with specific ecological and socioeconomic features when assessing its impact on the proportion of area burned. The proposed approach also extends the scope of former studies (e.g. Gonzalez and Pukkala 2007) by recognizing land use changes and by including socioeconomic variables in the analysis. This is instrumental to acknowledge key relationships between ecological and socioeconomic features and the proportion of area burned.

The analysis of the three sub-periods under study showed an overall increase in area burned for all the classes of fuel (cover type). This increase is mainly due to the large fires of 2003 in the third sub period that devastated around 440×10^6 hectares. The second sub-period was characterized by smaller area burned and has a relatively small number of fires, compared with the other two.

Modeling results underlined the impact of the land cover type on the proportion of area burned. Clearly, shrubs were the cover type that had higher impact on the proportion of area burned. This has also been indicated by other authors (Moreira et al., 2001, 2009; Nunes et al., 2005; Pereira, et al., 2006; Gonzalez and Pukkala 2007) and can be explained by a combination of both a higher rate of fire spread in this fuel type (both because of fuel properties and of its widespread occurrence in steeper slopes), a larger frequency of ignitions (e.g. to create pastures) and a lower fire fighting priority (Moreira et al., 2009). In contrast, annual and permanent crops were much less fire prone. This study further confirmed that hardwoods, either as pure or mixed stands, decrease the fire risk in forested areas, when compared to pine and eucalyptus stands. Moreira et al. (2009) explained these findings by differences in fuel load, moisture content and flammability in these different forests. In contrast, annual and permanent crops were much less fire prone. In short, this study confirmed that for most land-use classes, fire behaves selectively, with marked preference for shrub lands in terms of both fire number and fire size which is consistent with findings of other studies (e.g. Cumming 2001; Nunes et al. 2005; Bajocco and Ricotta 2008).

Slope is an important factor impacting fire behavior because it accelerates the rate of spread (Agee 1993). This probably explains the higher frequencies of fire found on steeper slopes. In relation to altitude, a recent paper (Catry et al., in press) showed that fire ignitions are more likely at higher altitudes, probably as a consequence of pastoral burns or a higher frequency of lightning. Again, this is consistent with our results of a higher proportion of burned areas for stratums at higher elevation.

The statistical analysis further showed that socioeconomic features such as the proximity to roads and population density impacted the proportion of area burned. Population density has been found to be the main driver of fire ignitions in Portugal (Catry et al., in press). Yet although fire ignitions in Portugal, as in other regions where fires are human-caused, are much more likely close to roads (Catry et al., in press), recent analysis (Romero-Calcerrada et al., 2010; Moreira et al., submitted) suggested that ignitions that resulted in large fires occur further away from roads. This is consistent with our results. The proportion of burned area increases with the distance from the road network, as accessibility (e.g. for fire fighters) is lower (Cardille et al., 2001; Vasconcellos et al., 2001; Badia-Perpinya and Pallares-Barbera 2006). Conversely, the proportion of burned area decreased with population density as lower densities may delay fire detection and increase the time before initial suppression operations.

In summary, the presented methodology was suitable to study the relationship between ecological and socioeconomic features with fire occurrence. Further, it provide insight needed to develop fire prevention policies. This study showed that emphasis has to be placed on fuel management as land cover has a substantial impact on the proportion of area burned. It confirmed that forest management may play a key role to successful fire prevention. Further research is needed in Portugal to translate these findings into information about specific management practices to diminish wildfire occurrence probability and wildfire damage.

I.6 – Acknowledgements

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Article II . Developing post-fire Eucalyptus globulus stand damage and tree mortality models for enhanced forest planning in Portugal

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II.1 - Abstract

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 perimeters 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 92 plots and 1858 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

II.2 - Introduction

Forest fires 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 thousand hectares per year has 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 Hull 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, Gonzalez 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, if the objective is to use mortality models for planning purposes, these models must be based on predictors whose future value is known with reasonable accuracy, and 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 may 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, Gonzalez 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,Hyytianinen 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. submitted). Eucalyptus 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 (NFI,2005). 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 Lemeshow1989, 2000). These methods have been previously used to predict the probability of a single tree to survive or die due to different causes (Monserud 1976, Botelho et al. 1996, Monserud and Sterba 1999, Linder et al. 1998, Guinto et al. 1999, McHugh and Kolb. 2003,Van Mantgem et al. 2003, Rigolot, 2004, Keyser et al, 2006, Gonzalez et al. 2007, Crecente-Campo et al, 2009). However, traditional modeling approaches generate mortality on all plots (Fridman and Stahl 2001). Moreover, many studies predict the mortality rate without distributing mortality among trees in the stand.

When applying logistic mortality 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 (Gonzalez et al. 2007, Fridman and Stahl 2001).

In this research, a three-step modelling strategy was used to develop the post-fire stand damage and tree mortality models (Woollons 1998, Fridman and Stahl 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 92 plots and 1858 trees were used for modeling purposes. Models with good ecological behavior were preferred over models with purely good statistical fit.

II.3 - Materials and methods

II.3.1 - Material

The fire data used in this study consisted of perimeters of 2006 to 2008 wildfires 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. 10 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 perimeters using GIS tools (ArcGIS 9.2) (Fig. 1). In total, this analysis showed that 10 eucalypt plots out of the 12237 NFI plots were burned between 2006 and 2008. 75 additional burned plots in eucalyptus ‘stands, were considered. The total 85 plots were located in 19 fires perimeters.

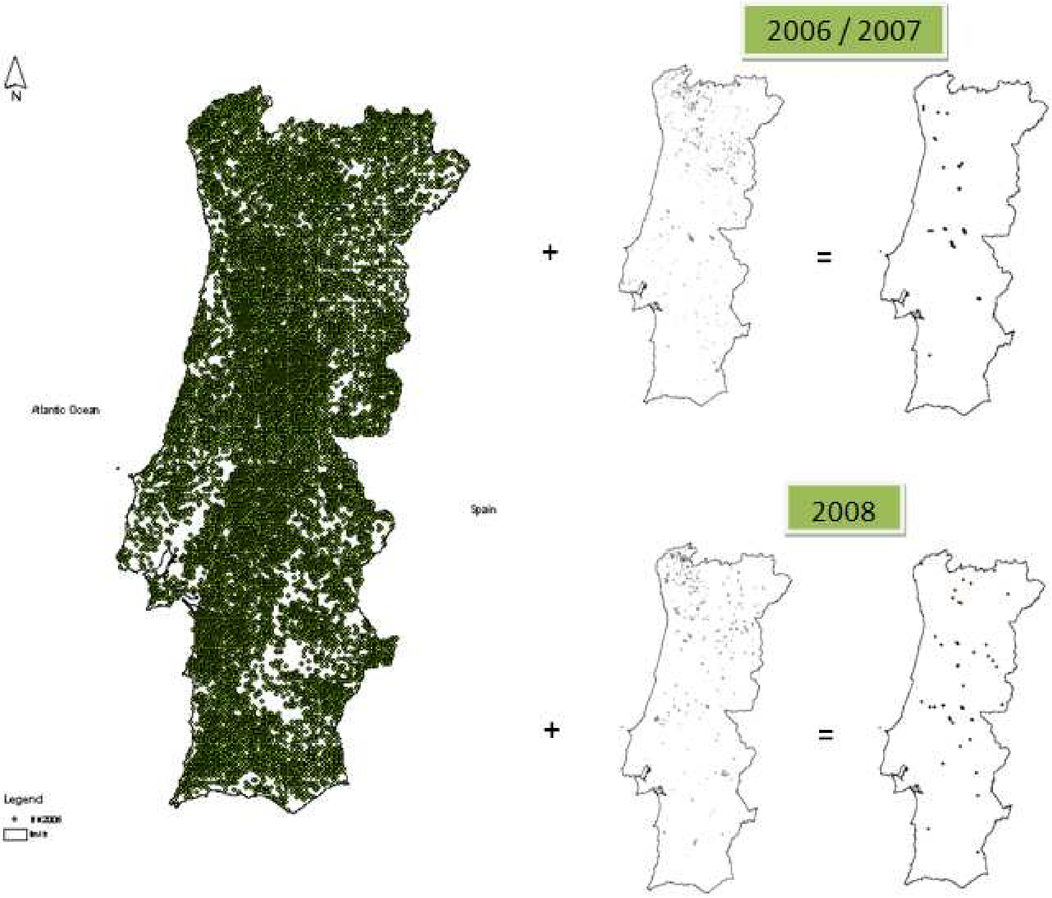

Figure II.1 - Locating inventory plots for data acquisition. The map on the left shows the national forest inventory plots (≈12200); the maps on top-right show the fire perimeters in 2006-2007 and the 43 burnt eucalypt plots; the maps on bottom-right , show the fire perimeters in 2008 and the 42 burnt eucalypt plots.

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 canopy height, degree fire damage) and the characterization of the plot (e.g. elevation, aspect, slope, presence of soil erosion, shrubs species).

In the case of the 75 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. Equations developed by Soares and Tomé (2002) (Eq. 1) were used to estimate pre-fire height.

$$h = hd\left(1+\left(0.10694+0.02916\cdot\frac{N}{100}-0.00176\cdot d_{\max}\right)\cdot e^{0.0354\cdot hd}\right)\cdot\left(1-e^{-1.81117\cdot\frac{d}{hd}}\right) \tag{1}$$

Where N is the stand density (number of trees per hectare), d is diameter at breast height (cm), d_{max} is the maximum stand diameter (cm), h_d is the dominant height (m).

II.3.2 - Methods

II.3.2.1 - Predicting 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 (Hosmer and Lemeshow 1989). Moreover, the logistic function is mathematically flexible, easy to use, and has a meaningful interpretation (Hosmer and Lemeshow 2000). This method assigns ‘1’ to the event of death and a ‘0’ to the no death event. The logistic regression is presented as:

$$Y = \frac{1}{1+e^{-(\beta_0+\beta_1\cdot x_1+\ldots\beta_p\cdot x_p+\varepsilon)}} \tag{2}$$

Where y is the dependent variable, x1 to xp are independent variables, β_0 is the intercept, β_1 to β_p, are estimated coefficients, and ε is the error term.

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, SAS Institute, Cary, NC) that estimates the parameters of the logistic equation with maximum likelihood methods 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.

II.3.2.2 - 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. A number of stand-level features (e.g. site conditions as altitude, slope, aspect, biometric variables as G (basal area), N (number of trees /ha), Dq (quadratic mean diameter (cm) of trees), Sd (standard deviation of trees diameter at breast height (cm)), Sh (standard deviation of trees height (cm)), DBH (tree diameter at breast height (cm)), Sd /Dq (relative variability of tree diameters), DBH/Dq (relative position of the tree within the stand (dominant or dominated)) were tested. Model building considered both the ecological consistency of predictors and its statistical significance (i.e. 0.05 significance level and no systematic errors in the residuals).

II.3.2.3 - Estimating stand-level damage caused by a wildfire

In order to quantify mortality caused by wildfires in stands where mortality did occur, a stand-level variable was created. This variable describes fire damage as the proportion of trees that will die in the stand as a consequence of a wildfire. 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. altitude, slope, aspect), biometric variables as G (basal area), N (number of trees /ha), Dq (quadratic mean diameter (cm) of trees), Sd (standard deviation of trees diameter at breast height (cm)), Sh (standard deviation of trees height (cm)), DBH (tree diameter at breast height (cm)), Sd /Dq (relative variability of tree diameters), DBH/Dq (relative position of the tree within the stand (dominant or dominated)) were tested. All predictors had to be logical and significant at the 0.05 level without any systematic errors in the residuals.

II.3.2.3 - 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. 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. In total, 1648 eucalypt trees were inventoried in burned plots, of which 771 had died as a consequence of the fire events.

This model used as a predictor the proportion of dead trees in the stand (Pd), an estimate of stand-level damage. Further predictors were selected by testing whether they improved the model. Selection further 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) and the analysis of the “receiver operating characteristic (ROC)” curve for testing the model sensitivity.

II.4 - Results

The logistic models to predict whether mortality will occur in a eucalypt (Eq. 3) stand are:

$$PMort = \frac{1}{1 + e^{-(\beta_0 + \beta_1 \frac{Sd}{Dq})}} \tag{3}$$

Where Pmort is the probability of stand death to occur, Sd is the standard deviation of trees’ diameters at breast height (cm), Dq is the quadratic mean diameter (cm) of trees. The predictor *Sd* /Dq expresses the relative variability of tree diameters.

The model indicates that higher values of *Sd*/*Dq* (i.e. variability of tree diameters) increase the probability of death to occur in the stand (Eq. 3). All model coefficients were significant, at least at the 0.05% level as judged by the Wald x^2 statistic (Hosmer and Lemeshow 1989) (Table 1). The model was successful in predicting whether mortality did occur after the wildfire in 63% of eucalypt stands (i.e. percentage of concordant pairs).

Table II.1 - Parameter estimates, standard errors (SE), Wald X^2 statistics and p-values for the model predicting predict whether mortality will occur in a stand (Eq. 5).

Effect	**Variable**	**Estimate**	**SE**	**Wald X^2**	**p>x^2**
β_0	Intercept	-1.1742	0.4716	6.1994	0.0128
β_1	Sd/Dq	3.8942	1.4944	6.7906	0.0092

The model indicates that relative damage increases when the ratio between Sd/Dq increases (Fig 2)

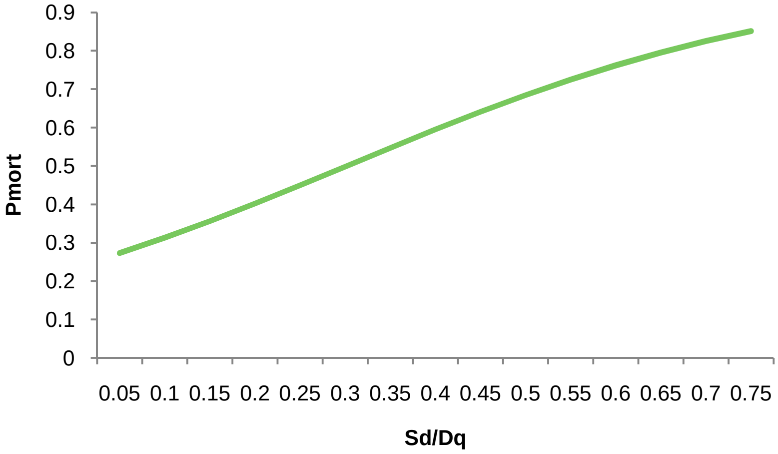

Figure II.2 – Effect of the stand structure (Sd/Dq) in the stand, i.e. the probability of mortality (Equation 3).

The models to quantify mortality caused by wildfires in eucalypt (Eq. 4) stands where mortality did occur are:

$$Pdead = \frac{1}{1 + e^{-(\beta_0 + \beta_1 \cdot Alt + \beta_2 \cdot Slope + \beta_3 \cdot G + \beta_4 \cdot Sd)}} \qquad (4)$$

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

All coefficients in Eq. 4 were significant, at least at the 0.05% level as judged by the Wald x^2 statistic (Hosmer and Lemeshow 1989) (Table 2), while 65% of the data were successfully identified by the model as to whether death had or had not occurred for eucalypt. Collinearity statistics were calculated for all the predictors and they showed no significant multicollinearity.

The model indicates that relative damage increases when stand basal area increases (Fig 3). Moreover, steep slopes and higher altitudes contribute to high fire damage (Eq.6).

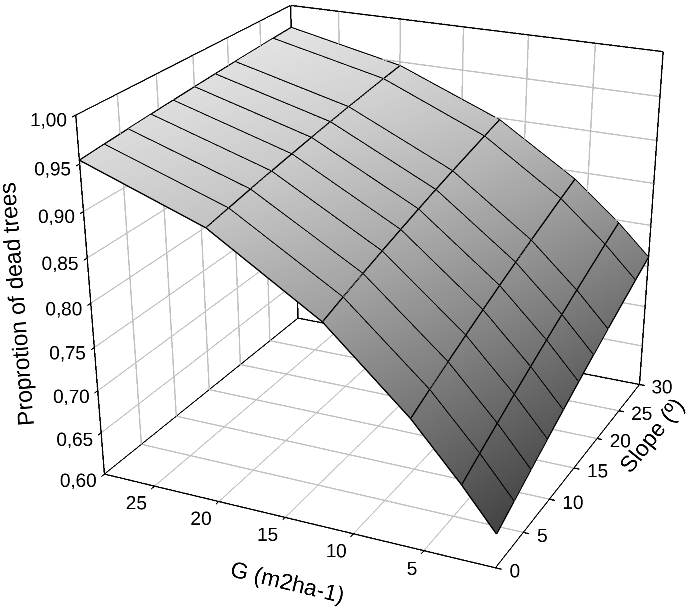

Figure II.3 – Effect of stand basal area (G) Slope on the degree of damage in the stand, i.e. the proportion of dead trees (Equation 4). The values were calculated with an altitude= 200 m and Sd = 3.47 cm.

Table II.2 - Parameter estimates, standard errors (SE), Wald X^2 statistics and p-values for the model predicting degree of damage caused by a widlfire (Eq. 4).

Effect	**Variables**	**Estimate**	**SE**	**Wald X^2**	**p>x^2**
β_0	Intercept	0.4654	0.0495	88.5417	<0.0001
β_1	Altitude	0.00119	0.000133	80.4201	<0.0001
β_2	Slope	0.0214	0.00278	59.2655	<0.0001
β_3	G	0.0401	0.0052	59.3581	<0.0001
β_4	Sd	-0.1027	0.0103	100.3593	<0.0001

A tree-level mortality model predicting the probability of a tree to die due to a forest fire was developed for eucalypt (Eq. 5):

$$PTreedie = \frac{1}{1+e^{-(\beta_0+\beta_1 \cdot DBH+\beta_2\frac{DBH}{Dq}+\beta_3\frac{Sd}{Dq}+\beta_4 \cdot Pd)}} \tag{5}$$

Where *Ptreedie* is the probability of a tree to die, *DBH* is the tree diameter at breast height (cm), Dq is the quadratic mean diameter (cm) of trees, *Sd* is the standard deviation of the diameter at breast height (cm) and Pd is the proportion of dead trees. The predictor *DBH/Dq* expresses the relative position of the tree within the stand (dominant or dominated). The higher the value of this variable the more dominant the tree is. The predictor *Sd /Dq* expresses the relative variability of tree diameters.

All coefficients in Eq. 5 were significant, at least at the p<0.05 level (Table 3) as judged by the Wald x^2 statistic (Hosmer and Lemeshow 1989).

Table II.3 - Parameter estimates, standard errors (SE), Wald X^2 statistics and p-values for the tree-model predicting the probability of a tree to die due to a forest fire (Eq.5).

Effect	**Variables**	**Estimate**	**SE**	**Wald X^2**	**$p>x^2$**
β_0	Intercept	-2.9465	0.3995	54.4043	<0.0001
β_1	DBH	-0.137	0.0373	13.5118	0.0002
β_2	DBH/Dq	-1.7008	0.5991	8.0605	0.0045
β_3	Sd/Dq	6.5436	0.9446	47.9917	<0.0001
β_4	Pd	9.7179	0.5193	35.2179	<0.0001

The model predicted the right outcome (death after the wildfire) in the case of 98.9% of inventoried dead trees. The area under the ROC curve (0.868; Fig 4) indicates excellent discrimination (Hosmer and Lemeshow 2000), thus showing that the selected model performs well.

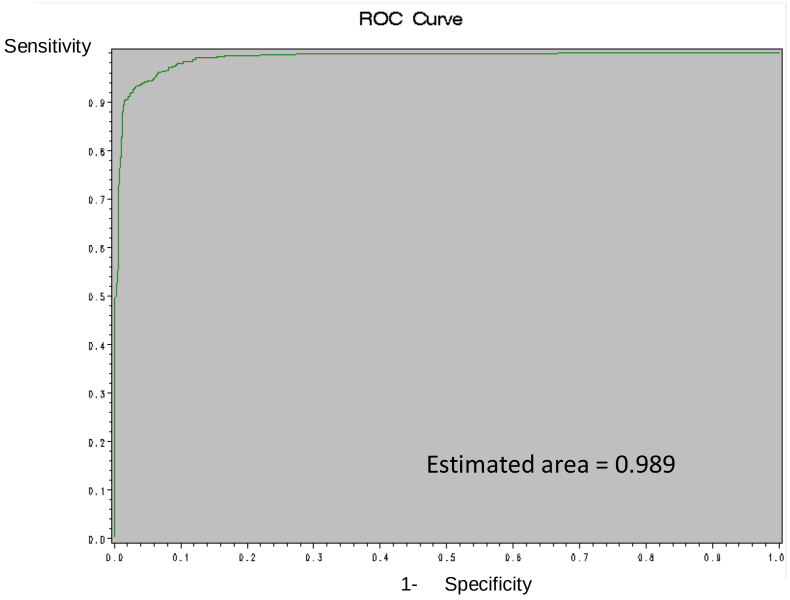

Figure II.2 – ROC curve for Eucalypt tree-mortality model.

The model (Eq. 5) indicates that trees with high diameters and trees in dominant positions (high DBH/Dq) are less prone to die when a wildfire occurs (Fig 5).

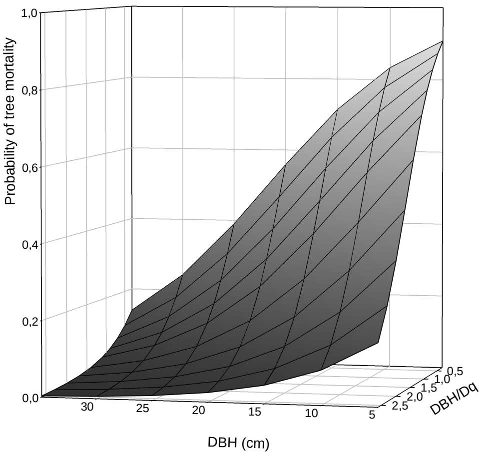

Figure II.5 - Effect of tree-diameter (DBH) and forest structure (DBH/Dq) on the probability of tree mortality using equation 5. The predictor DBH/Dq expresses the relative variability of tree diameters. The higher the value of this predictor the higher tree variability. The values were calculated using **Sd/Dq** =1 and Pd=0.467 which are the mean values of our dataset

Moreover, trees located in stands with regular structure (lower variability of stand diameters, Sd/Dq) and lower expected stand damage (Pd) have also lower mortality probability (Fig. 5).

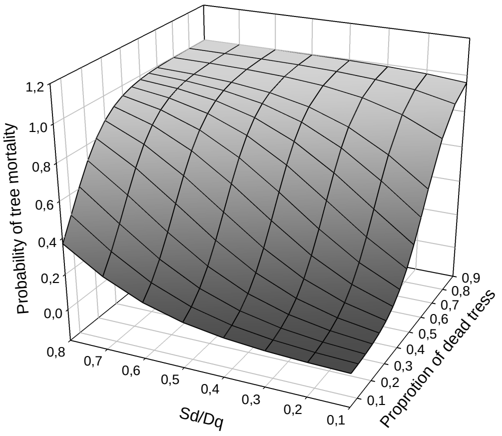

Figure II.6 - Effect of proportion of dead trees at stand level and tree diameter (DBH) on the probability of tree mortality using equation 5. The values were calculated using dbh/dq=1 and Sd/Dq= 0.3 which are the mean values of our dataset.

II.5 - Discussion and conclusions

A variety of methods have been used to study post-fire mortality (e. g. Fowler and Hull 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. The proposed logistic modeling approach overcomes these obstacles and it 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, Harrington1993, Stephens and Finney 2002, Beverly and Martell 2003, McHugh and Kolb 2003, Rigolot 2004, Gonzalez et al. 2007). This approach has been also used to model natural tree mortality (Fridman and Stahl 2001, Alvarez-Gonzalez 2004). 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, Hyytiainen and Haight 2009).

The proposed approach was tested using a large dataset encompassing 1648 trees in 85 plots located in 19 fire perimeters in Portugal. Results suggest that the models may predict accurately post-fire damage in Eucalypt stands in Portugal. In the framework of forest management planning, equation 3 may be used to predict whether mortality may occur in a stand after a wildfire. If mortality is predicted to occur, equations 4 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 equation 5. As suggested by Gonzalez 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.

Biometric variables selected for estimating post-fire mortality included the tree diameter (DBH), the relative variability of tree diameters (Sd/Dq and Sd), basal area (G) and the predictor of tree position within the stand (DBH/Dq). 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 damage. This is in concordance with other studies and may be explained by an easier transfer of heat uphill (Agee 1993, Gonzalez et al 2007, Hyytiainen and Haight 2009). In our case, altitude correlates positively with the degree of damage 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 (Malcolm 1977). Moreover, the eucalypt mortality models also showed that in stands with higher densities, fire damage is expected to be higher than in stands with lower densities. These results are in concordance with findings from other studies (Guinto et al. 1999, Pollet and Omi 2002, Gonzalez 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. This is in concordance with other studies (Ryan and Reinhardt 1988, Linder et al. 1998, Gonzalez et al. 2007). Monserud and Sterba (1999) indicated that competition can be expressed indirectly by the stand density e.g. basal area, and directly by indices that reflect the competition between individual trees e.g. BAL (the basal area of all trees larger than the subject tree). In our case, tree competition is included in the Eucalyptus model as DBH/Dq. This variable indicates the relative position of the tree within the stand. The coefficient of this predictor is negative which indicates that dominant trees are less prone to die than dominated trees. This finding is also coherent with other studies (Van Mantgem et al. 2003, Gonzalez et al. 2007), dominant trees experiencing less competitive stress than smaller ones. Moreover, stand density was found to be positively related with tree mortality. This is in concordance with findings by Fernandes and Rigolot (2007) and Greenwood and Weisberg (2008). 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 period extending over an average of 1 year after the wildfire. In some cases, this may lead to an underestimation of mortality caused by the wildfire. Nevertheless, the development of the first post-fire mortality models in Portugal took into account all available data and information.

Fire damage models (e.g. Beverly and Martell 2003, Gonzalez 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. Thus, we may conclude that these models are instrumental to designing silvicultural strategies that may decrease the damage caused by wildfires.

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.

II.6 – Acknowledgements

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Conclusions

Wildfires threaten people, destroy urban and rural property and damage forest resources. They have increased their number and area, on the Mediterranean Basin, especially in Portugal, in the three last decades. This context suggests the need for the development of effective fire prevention policies. These two studies were developed to fill the lack of information about the fire behavior and management and develop scientifically sound methods that can be used by the public administration, non-industrial forest owners, industry and non-governmental organizations for enhanced integration of forest and fire management planning activities.

On the first study, thru generalized linear models we got three mathematical models or equations for different periods (1987-1991, 1990-1994 and 2000-2004), that allow the estimation of the fire incidence probability, in different land use cover types, topography and socio-economic characteristics as altitude, slope aspect, roads proximity and population. In summary, the methodology used was suitable to study the relationship between ecological and socioeconomic features with the fire occurrence. Further, it provides insight needed to develop fire prevention policies. This study shows that emphasis has to be placed on the fuel management as shown by the different fire occurrence depending on the land cover. In this sense, forest management can be an efficient tool for fires prevention. Further research is needed in Portugal to analyze how to diminish risk of fire probability and fire damage with forest management

The main objective of the second study was to develop models to predict the damage or losses caused by forest fires, on eucalyptus pure stands. Specifically, the developed models assessed wildfire mortality probability. 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), and that are easily measurable or calculated thru growth models.

They provide information about the impact of forest fires under alternative forest conditions. Thus, we may conclude that these models are instrumental to designing silvicultural strategies that may decrease the damage caused by wildfires. Thus we may further conclude that they can be used to integrate effectively fire risk into forest management planning.

This work was written in article format, where each submitted articles is one chapter. These articles are structured following the journals indications and they were submitted to Annals of Forest Science (first study) and to Silva Fennica (second study). The author of this thesis, first author of the articles, and was the person who mainly develop the studies. The co-authors of both articles, helped during the data treatment, statistic analysis and article redactions.

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Annexes