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# Tree Mortality Models for *Pinus pinaster* of Northern Portugal

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**Abstract.** The use of prescribed burning as a tool for forest fire prevention is becoming a more common practice in *Pinus pinaster* plantations of Northern Portugal. Prescribed fire is used to reduce the understory vegetation with the goal of reducing fuel hazard and the potential for stand-destroying wildfires.

A research program has been carried out for the purpose of understanding how fire injury contributes to tree mortality, to predict potential tree survival after fire for different levels of crown and stem injury, to use fire effects information in the planning and management decisions affecting protection of pine plantations from fire damage, and to provide information for successful prescribed burning.

Mortality was followed in trees from 12 plots burned in winter time under varying environmental conditions. The objectives of the study were to determine the impact of different levels and types of fire injury on individual tree mortality and to develop models for predicting survival of burned trees.

Non-linear, logistic and exponential regression models were developed to predict postfire tree mortality as a function of the following fire injury and heat resistance variables: ratio of crown length scorched to prefire crown length (RCs), proportion of prefire crown volume scorched (Csv), and diameter at breast height. One- and two-variable models were developed.

The results indicate that fire injury decreased with increasing dbh and increased with increasing RCs or Csv. RCs predicted slightly better than Csv, but Csv is an easier variable to obtain. Both RCs and Csv predicted mortality more accurately than dbh. Once crown injury was accounted for in the model the addition of dbh only made small improvement in predicted mortality. Logistic regression models performed slightly better than exponential models except at extreme injury values.

The equations derived from this study are suitable for predicting mortality following fire damage in similar stands. And they provide insights necessary for developing safe burning prescriptions of *Pinus pinaster* plantations.

## Introduction

In regions where the expected fire return interval is relatively short when compared to the planned harvest age, some type of treatment such as mechanical, grazing, or fire is needed to reduce the amount of litter, herbaceous, and shrub fuels. Without fuel treatment the risk of a stand-destroying wildfire occurring prior to harvest is unacceptably high.

Pines are indigenous to many regions of the world where periodic fires are common. Many species exhibit traits such as thick bark, high-open crowns, large or shielded (e.g., epicormic) buds, deep rooting, and serotinous cones which adapt them to varying degrees of fire. *Pinus pinaster* from Portugal exhibits such fire-resistant morphological characteristics (Ryan *et al.* 1994a,b).

Bark thickness is widely recognized as the primary factor determining a tree's resistance to cambial injury (Harmon, 1984; Green & Schiling, 1987; Ryan & Reinhardt, 1988). Bark thickness increases approximately linearly with tree diameter and resistance to fire injury increases with the square of the bark thickness (Peterson & Ryan, 1986; Rego & Rigolot, 1990). Thus resistance to cambium injury can be expected to increase with the square of stem diameter (Ryan & Reinhardt 1988). Cambial injury is related primarily to the duration of heating and less so to the intensity of heating. Some authors (e.g., Ryan *et al.*, 1988; Duhoux, 1994) have used point samples of cambium condition (i.e., live versus dead) to estimate the number of quadrants with dead cambium. However, because quantification of cambium injury requires destructive sampling, the height, severity, or percentage of trunk charring are often used as surrogates for actual cambium injury in models of tree mortality (Dixon *et al.* 1984;

Waldrop & Van Lear, 1984; Peterson, 1984; Peterson & Arbaugh, 1986, 1988; Wyant *et al.* 1986). *Pinus pinaster* is a relatively thick-barked tree showing good resistance to fire injury at an early age (Ryan *et al.* 1994a,b)

Height of crown scorch is correlated with fireline intensity (Van Wagner, 1973). Scorch height is an extremely useful variable for specification in burning prescriptions (Bevins, 1980) but is not as good a predictor of mortality as the volume of crown scorched (Wyant *et al.* 1986, Peterson, 1985; Ryan & Reinhardt, 1988; Ryan *et al.* 1988). Thus the probability of mortality is better explained by the effective foliage injury than by fire behavior per se. If buds and twig cambia survive, scorched foliage may be replaced if the branch has sufficient carbohydrate reserves. If not, the loss of photosynthetic surface is permanent resulting in an imbalance between the tree's demand for carbohydrates and their supply. Heat resistance depends on bud size and burn season (Byram, 1948; Wagener, 1961; and Peterson & Ryan, 1986). For example, *Pinus ponderosa* buds are large and heat resistant (Ryan, 1993), but vulnerable to fire damage in the growing season (Wagener, 1961). Coniferous species can withstand crown kill better during the dormant season (De Ronde *et al.*, 1986). Duhoux (1994) found that *Pinus pinaster* buds were less sensitive to heat than needles. Thus *Pinus pinaster* is a high heat-resistant species. Crown scorch is qualitatively assessed by visual estimation of the percentage of crown volume scorched (Wagener, 1961, Mitchell & Martin, 1980; Ryan, 1982; Peterson, 1984; Ryan *et al.* 1988, 1994b; Ryan & Reinhardt, 1988; Ryan, 1993; Saveland & Neuenschwander, 1990; and Duhoux, 1994); by measurement of the crown length scorched (Wyant *et al.* 1986; Pageaud, 1991; Duhoux, 1994); and by height of crown scorch (Bevins, 1980; Saveland *et al.*, 1990).

Root injury is often associated with fire and can be an important factor explaining tree mortality (Ryan 1989) but root injury is rarely described in the literature due to the difficulty of assessing root distribution (Swezy & Agee, 1991; Wade, 1986). Duff, and to a lessor extent dry mineral soil, are good insulators and protect roots from surface fire heat. Dry duff, however can burn for several hours (Ryan & Frandsen, 1991). The duration of burning rather than the intensity of the surface fire is the primary factor affecting root injury. In the absence of duff the depth of lethal heat penetration is minimal. However, as duff accumulates fine roots permeate the duff and coarse roots develop nearer the surface (Kramer & Koslowski, 1972, Fischesser, 1981; Wade, 1986). These superficial roots can be killed by heat from burning of duff and logs. If only fine roots are injured a vigorous tree can be expected to survive in good environmental conditions (Chambers *et al.*, 1986). *Pinus pinaster* has a deep lateral-branched rooting habit (Maugé, 1987) which should make it relatively resistant to fire injury.

Tree mortality can result directly from fire killing excessive amounts of foliage, bud, cambium, or root tissues either singlely or in combination. It also may occur if fire injuries stress the tree physiologically to the point where it is unable to survive subsequent insect or disease attack, or unfavorable weather. Tissue injury occurs when the intensity or duration of heating exceed the tissues' thresholds for injury. Tree mortality occurs when excessive amounts of tissue are destroyed. Mortality may be instantaneous and obvious as is often the case in a crown fire. Conversely it may be delayed and subtle as sometimes occurs when smoldering duff either girdles the root crown or excessively prunes roots. Trees with sub-lethal tissue injuries have an increased likelihood of successful insect attack (Ryan & Amman, 1993).

Given the difficulty of adequately quantifying tissue injury, particularly in cambia and roots; the uncertainty of insect or disease attack; and the unpredictability postfire weather, we will never be able to predict with certainty the fate of burned trees. However, with careful observation of fuels, fire behavior, tissue injury, and postfire survival we can develop models to predict the probability of mortality to a degree of accuracy sufficient to support the use of prescribed burning in the management of pines in fire-prone areas (Ryan, 1991). The objective of this study was to measure and model postfire survival of *Pinus pinaster* in Northern Portugal.

## Methods

Prescribed burns were conducted in 12 *Pinus pinaster* plantations from three areas in Northern Portugal: 1. Northern Interior (Serra da Padrela, Tras-os-Montes); 2. Littoral (Serra de Vieira e Monte-Crasto, Minho); and 3. Central Portugal (Serra da Lousa, Beira Litoral). Plots were located in mountainous areas. Annual precipitation is around 1500mm and falls mainly from December to March. Fuels in the plantations consisted of pine litter and abundant shrubs (*Erica* spp., *Chamaespartium tridentatum*, and *Ulex europaeus*) The plantations were hand ignited with strip headfires and burned surface fuels. Postfire survival was monitored for two years on 927 trees ranging in size from 2.9 to 12.3 cm diameter breast height and 2.7 to 10.1 m tall. Fires were burned in the dormant season. Fireline intensity ($I_B$, Byram, 1959) ranged from 85.2 to 854.4 kW $m^{-1}$. Scorch heights varied from 0.97 to 9.25 m. Additional details are contained in Botelho (1996).

The following variables were measured: diameter breast height (Dbh), cm; height of crown scorch (Hs), m; and the proportion of the crown volume scorched (Csv). Scorch was measured two weeks after burning, once the foliar damage was apparent (i.e., when the scorched foliage turned brown). Hs was recorded as the average between the lowest and highest level measured from the ground to the height of the visibly scorched needles. From this the ratio of the crown scorched (RCs) was calculated, as the average length of the foliage scorched and expressed as a proportion of the prefire live crown length. Csv was visually estimated.

Logistic regression analysis was used to choose the predictive variables using SAS PROC LOGISTIC (SAS Institute, 1990). Signal Detection Theory (SDT) and Receiver Operating Characteristic (ROC) analyses were used to evaluate the predictive performance of the models and for comparison between models (Egan, 1975; Saveland & Neuenschwander, 1990; MacMilan & Creelman, 1991; Rego & Machado, 1994). Concordance was used to measure the association between predicted probabilities and observed conditions. The logistic models obtained are of the form:

$$Pm = \frac{1}{1 + exp^{\,(b_0+b_1X_1+b_2X_2)}}$$

Because for the extreme values of 0 and 1.0 the logistic function tend for $-\infty$ for high values of the independent variable and to $+\infty$ for the lower values, we never obtain 0 or 1.0 of mortality, which is not realistic. So, we also used other non-linear regressions, of an exponential function, with a data transformation to force the curves to pass through the minimum and maximum (0 and 1.0).

Univariate models for RCs and Csv are:

$$Pm = exp\,(K\,\frac{X-1}{X})$$

and for dbh:

$$Pm = exp\,(K\,\frac{X}{X-15})$$

and the bivariate model:

$$Pm = exp\,(K\,\frac{X_1-1}{X_1}\;\frac{X_2}{X_2-15})$$

## Results

The coefficients and concordance values for the logistic regression models are in Table 1.

Table 1.

| Variables | | Coefficients | | | Concordance |
|---|---|---|---|---|---|
| $X_1$ | $X_2$ | $b_0$ | $b_1$ | $b_2$ | |
| dbh | - | -1.5497 | 0.5275 | - | 86.4 |
| Csv | - | 11.0398 | -11.9199 | - | 92.4 |
| RCs | - | 10.5692 | -12.7344 | - | 94.1 |
| Csv | dbh | 7.3895 | -10.1189 | 0.3809 | 95.3 |
| RCs | dbh | 7.5328 | -10.6616 | 0.2643 | 95.0 |

Csv and RCs (0 to 1.0); dbh in cm. The coefficients ($b_0$, $b_1$, $b_2$) are significantly different from 0 with probability < 0.05.

The coefficients for the exponential models are in Table 2.

Table 2.

| Variables | | Coefficient | Concordance |
|---|---|---|---|
| $X_1$ | $X_2$ | $k$ | |
| Csv | - | 14.1031 | 92.2 |
| RCs | - | 4.1740 | 93.5 |
| dbh | - | 2.9904 | 86.0 |
| Csv | dbh | -24.1395 | 94.0 |
| RCs | dbh | -10.3060 | 93.8 |

Csv and RCs (0 to 1.0), dbh in cm.

The predicted mortalities for the logistic and exponential models are compared for dbh (Figure 1) and RCs (Figure 2). Both logistic and exponential models predict similar mortalities. And concordance values are also similar. The maximum difference in predicted mortality between logistic and exponential models was about 0.1. Logistic models tended to under predict mortality at extreme crown injury. RCs performed marginally better than Csv. Once either Csv or RCs is in the model adding dbh resulted in only minor improvement in model performance (Tables 1 and 2). The receiver operating curve indicates both models performed similarly (Figure 3).

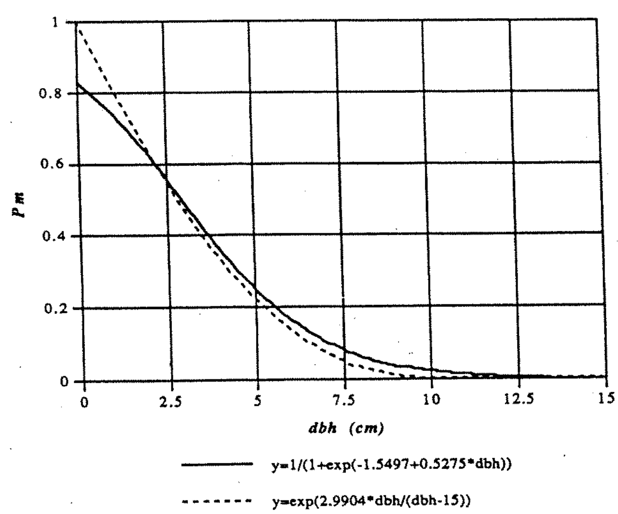


**Figure 1.** Prediction of Mortality as a function of dbh for logistic and exponential models.

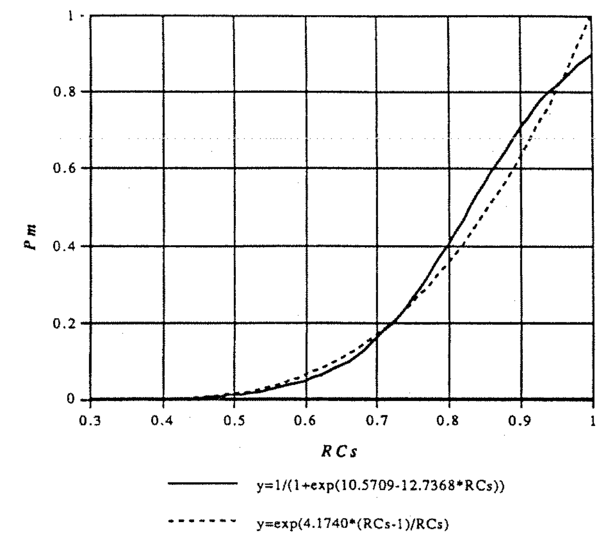


**Figure 2.** Prediction of Mortality as a function of RCs for logistic and exponential models.

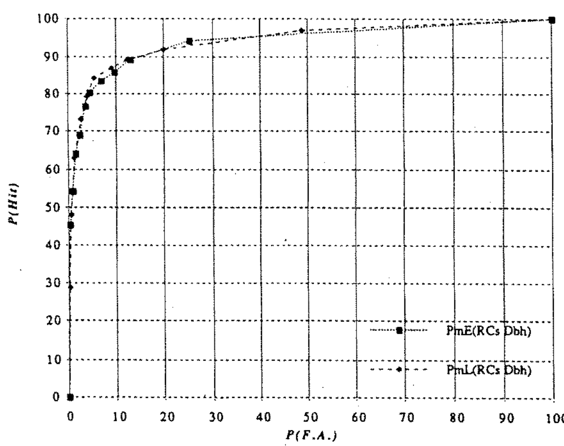


**Figure 3.** An example of a ROC curve for comparing the two different models (logistic and exponential) for RCs and dbh.

## Discussion

Reliable models are needed to support prescribe burning decisions. These models must be based on easily assessed parameters. When planning a prescribed burn it is necessary to predict both the fire's behavior and the injuries it will cause. It is also necessary to know how the trees will respond to these injuries. Mortality decreased with increasing diameter as expected. Larger trees have both thicker more fire resistant bark and higher crowns, which are less likely to be severely scorched. Cambium damage depends on combustion residence time and bark thickness. Root damage is probable when heavy fuel accumulations burn or trees have superficial roots. The weather and fuel conditions of these burns were not suitable for releasing much heat down into the soil. The shrubs and litter burned quickly and the soil was relatively moist. The duration of burning in these prescribed fires was less than the critical time for killing the cambium and roots of the trees. The equations based on dbh can be used to establish limits for burning *Pinus pinaster* plantations under similar fuel, season, and weather conditions. If, however, fuel and environmental conditions vary significantly from those in this study fire behavior and injury will also vary and mortality cannot be reliably predicted from diameter alone.

When developing burning prescriptions mortality models based on fire injuries such as crown scorch are less useful than tree diameter models because the model's independent variable, fire injury, must be predicted rather than observed. Once a fire has occurred observable fire injuries invariably provide better predictive relationships than measures of tree size. The Csv and RCs equations can be used reliably to predict postfire survival from areas burned by fires of similar duration. For relatively thick barked species like *Pinus pinaster* models based on crown injury alone predict well except in long duration fires such as the burning of logging slash or deep duff (Ryan 1982, 1989). While models based on RCs were slightly better than those based on Csv, it is much easier to ocularly estimate Csv than to measure RCs.

Numerous authors have used logistic regression models to predict mortality (Bevins, 1980; Peterson, 1984; Peterson & Arbaugh, 1986, 1988; Ryan *et al.* 1988, 1994b; Ryan & Reinhardt, 1988; Saveland & Neuenschwander, 1990; Finney & Martin, 1993). When the data used to construct the model are well distributed throughout the independent variable's ranges and there is a good mix of surviving and dying trees, logistic models perform well. If these conditions are not met it is often difficult to get convergence to zero or one at the extremes of independent variable's range. The use of an exponential model provides a practical solution to this problem. In this study the data were robust and the two approaches yielded similar results.

## Conclusions

Both univariate and multivariate models reliably predicted post fire mortality of plantation grown *Pinus pinaster* from Northern Portugal. Actual fire injury (Csv or RCs) performed better than tree size (dbh). However, the dbh model is the best model for prefire decisions. Although the univariate and bivariate models based on RCs performed better than Csv, the latter is recommended for postfire management decisions because it is easier to apply. Logistic and exponential models both performed about as well.

Better knowledge of the fire behavior and its relationship to tree injury is needed for developing burning prescriptions. Better understanding is also needed on how trees physiologically respond to fire injury. Until we develop a mechanistic understanding of fire's energy release characteristics and how heat is transferred to tree tissues we will not be able to adequately predict fire injury. Until we develop an improved understanding of the physiological consequences of fire injury we will have a limited ability to predict survival. Until we develop these fundamental understandings we need to rely on empirical field studies such as this one to generate predictive models. Use of these models is limited to similar conditions but they provide adequate guidance for local fire use decisions.

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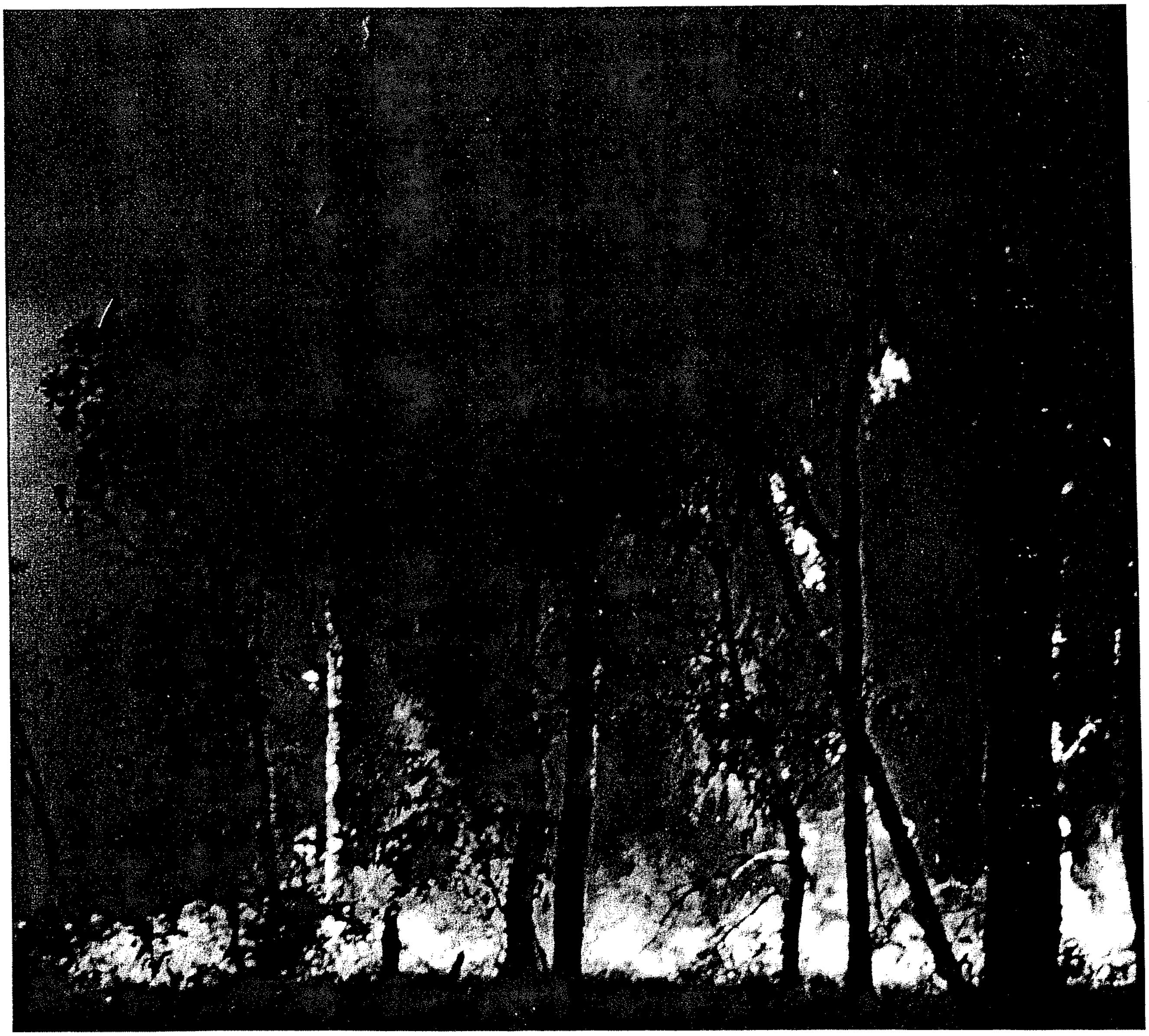

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