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EMPIRICAL MODELS FOR DESCRIBING FIRE BEHAVIOR IN BRAZILIAN COMMERCIAL EUCALYPT PLANTATIONS

ABSTRACT: Modeling forest fire behavior is an important task that can be used to assist in fire prevention and suppression operations. However, according to previous studies, the existing common worldwide fire behavior models used do not correctly estimate the fire behavior in Brazilian commercial hybrid eucalypt plantations. Therefore, this study aims to build new empirical models to predict the fire rate of spread, flame length and fuel consumption for such vegetation. To meet these objectives, 105 laboratory experimental burns were done, where the main fuel characteristics and weather variables that influence fire behavior were controlled and/or measured in each experiment. Dependent and independent variables were fitted through multiple regression analysis. The fire rate of spread proposed model is based on the wind speed, fuel bed bulk density and 1-h dead fuel moisture content ($r^2 = 0.86$); the flame length model is based on the fuel bed depth, 1-h dead fuel moisture content and wind speed ($r^2 = 0.72$); the fuel consumption proposed model has the 1-h dead fuel moisture, fuel bed bulk density and 1-h dead dry fuel load as independent variables ($r^2 = 0.80$). These models were used to develop a new fire behavior software, the "*Eucalyptus Fire Safety System*".

MODELOS MATEMÁTICOS EMPÍRICOS PARA DESCREVER O COMPORTAMENTO DO FOGO EM PLANTAÇÕES COMERCIAIS DE EUCALIPTO NO BRASIL

RESUMO: A modelagem do comportamento do fogo consiste em uma importante tarefa que pode ser utilizada para atividades de prevenção e combate. Entretanto, com base em estudos anteriores, os modelos comumente utilizados em outros países não o estimam corretamente nos plantios de eucalipto híbrido no Brasil. Sendo assim, este estudo teve por objetivo construir novos modelos empíricos para estimar a velocidade de propagação, comprimento das chamas e consumo do material combustível para o fogo dentro da respectiva vegetação em questão. Para tal, 105 queimas laboratoriais foram realizadas em que as principais características meteorológicas e do material combustível que poderiam interferir no comportamento do fogo foram controladas e/ou medidas. Variáveis dependentes e independentes foram correlacionadas por meio da regressão multivariada. O modelo para a velocidade de propagação proposto baseou-se na velocidade do vento, densidade do leito e no teor de umidade do material combustível de 1h de *timelag* ($r^2 = 0,86$); o modelo para o comprimento das chamas baseou-se na espessura do leito, no teor de umidade do material combustível de 1h de *timelag* e na velocidade do vento ($r^2 = 0,72$); o modelo para o consumo do material combustível teve como variáveis independentes o teor de umidade do material combustível de 1h de *timelag*, a densidade do leito e a carga do material combustível de 1h de *timelag* ($r^2 = 0,80$). Os modelos construídos serviram de base para o desenvolvimento do *software* "*Eucalyptus Fire Safety System*".

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INTRODUCTION

Understanding how fire will behave is one of the key parameters in order to develop an effective program of fire prevention and suppression, or even for the use of the prescribed burn technique.

In the 1940's mathematical models to describe fire behavior began to be developed and, until the year 2000, 43 different surface fire behavior models had been created in 10 different countries (PASTOR et al., 2003). So far, the Rothermel (1972) fire spread model is the most used in the world for estimating the surface fire rate of spread (PASTOR et al., 2003; WELLS, 2008; ANDREWS, 2010). This model has been incorporated into many programs, such as BehavePlus (ANDREWS et al., 2002), an update of the original BEHAVE (ANDREWS, 1983), that, according to Andrews (2010), is the leading fire behavior predicting system in the USA. A second important model often used in conjunction with Rothermel (1972) is the Byram (1959) model, both models has been widely used in a range of ecosystems and fuel beds for decades (PERRY, 1998).

Specific fire behavior studies in Eucalyptus have been done mostly in Australia's native forest (e.g. MCARTHUR, 1962; PEET, 1965; MCARTHUR, 1967; BURROWS, 1994; BURROWS, 1999; ELLIS, 2000; GOULD et al., 2007; CHENEY et al., 2012; MCCAW et al., 2012). Modelling studies began with the work of McArthur (1962) who, using controlled burns, designed meters for determining the surface fire behavior. Later, McArthur (1967) designed other meters for wildfires, which were fitted into equations (NOBLE et al., 1980) and incorporated into a software: CSIRO Fire Danger and Fire Spread Calculator (CSIRO, 1999). Despite all these studies, a lack of knowledge remained of how fire behaves in eucalypt plantations outside its natural habitat.

Besides assisting in fire suppression, mathematical fire behavior models are constantly used in prescribed burn activities. A wide range of objectives can be accomplished by applying prescribed burns in eucalypt plantations, including reducing wildfire risk/hazard; site preparation for tree regeneration; silvicultural improvements; range and wildlife habitat management; control of weeds, insects and diseases; and biodiversity maintenance (WADE; LUNSFORD 1989; FERNANDES; BOTELHO, 2003).

For decades, fuel management activities in eucalypt have been done only in Australia's native forests (e.g. MCARTHUR, 1962; CHENEY et al., 1998; BUCKLEY; CORKISH, 1991). Nevertheless, new studies in commercial plantations in Portugal, the FIREglobulus project (PINTO et al., 2014), proved the efficiency of prescribed burns in reducing available fuel load, and consequently reducing the wildfire hazard.

If it is known how the fire will behave, controlled burns can be prescribed as a preventive wildfire method for protecting forests; wildland resources and infrastructures; and even human lives. In Brazil, annual economic losses caused by fires in eucalypt plantations are quite high and justify the use of the prescribed burn technique. Santos et al. (2006) calculated that between 1998 and 2002, 5,832 fires occurred in eucalypt plantations in the country. This amount represents 30% of all fires in all vegetation types recorded, and accounted for a burnt area of 13,562 hectares, 16% of the total area burned during the period.

Since previous studies concluded that the Rothermel (1972), Byram (1959) and McArthur (1962) models underestimate significantly the fire rate of spread and flame length in Brazilian commercial eucalypt plantations (WHITE et al., 2016), there is a need to build new mathematical models that can better predict those fire behavior variables and also, assess the fire fuel consumption, an important parameter for the use of the prescribed burn technique. Therefore, this study proposes new mathematical models for estimating fire rate of spread, flame length and fuel consumption.

MATERIAL AND METHODS

Laboratory burns

Nylon bags were used for carrying the fuel load from the field to a particular laboratory assembled in the city of Aracaju, Sergipe. The characterization of the 6-year-old commercial eucalypt plantations, where the fuel was collected, is described in White et al., (2014).

One hundred and five experimental burns were done to represent different ways that a fire can behave in eucalypt stands: dry season fires, rainy season fires, low or high fuel load, with and without influence of the wind. Therefore, the experimental burns were done with different arrangements of fuel load, bed depth and bulk density, and with variable meteorological conditions and fuel moisture content.

A burn table of 1.5 x 1.5 meters was installed in a semi open area (roofless, but with 3 meter tall sidewalls) with zero degree slope at ground level. The environmental wind was always from the same direction (east to west) and a divided sliding portal was used to control the speed. A drip torch filled with kerosene was used to ignite a 1.5 m width fireline located at the windward initial edge of the burn table.

When the fire reached the first line, set at 12.5 cm into the table, the timer was started. At the second, third, fourth, fifth and sixth lines the flame height, flame angle, flame length and wind speed were measured. Therefore,

the values of these four variables for each burn were determined from the mean of five measurements taken each 25 cm as the fire front passed. When the fire reached the sixth line, also called "end line", the timer was stopped and the rate of spread determined (Figure 1).

The independent variables measured in this study were selected after an extensive bibliographic research from which the main factors that influence fire behavior were defined (Byram, 1959; McArthur, 1967; Rothermel, 1972; Brown; Davis, 1973; Gould et al, 2007; Soares; Batista, 2007; Fernandes, 2009; Cheney et al., 2012; Fernandes; Loureiro, 2013). They are: 1-h dead fuel load; 10-h dead fuel load; total dead fuel load (1-h + 10-h); fuel bed depth (fuel height); fuel bed bulk density; 1-h fuel moisture; 10-h fuel moisture; air temperature; air relative humidity; and wind speed.

To determine the load and the moisture content of 1-h, 10-h and, therefore, the total dead fuel load for each experiment, the entire fuel, immediately before being burned, was separated according to the time-lag class and weighed. A small sample for each class was packaged in paper bags, weighed and dried in an oven at 100°C for approximately 24h until they reach constant weight. By knowing the moisture content, the dry fuel load was determined.

After, the fuel was homogeneously scattered onto the combustion table and the fuel bed depth was determined based on the mean of five random measurements. The fuel bed bulk density was set for each experiment by dividing the total fuel load by the mean fuel bed depth. The air temperature and relative humidity were recorded immediately before the burns. Both were obtained from a Weatherwise Professional Wireless Weather Station (Model: SW-1090-SOLAR) installed at the burn site at 2 m height. The wind speed was measured with a handheld anemometer (LUTRON

Electronic Enterprise Model: LM-8000) positioned right before the combustion table at eye level height.

Five aspects of fire behavior were analyzed: fireline intensity, heat per unit area, rate of spread, flame length and fuel consumption. Heat per unit area and fireline intensity were both calculated with Byram's (1959) equations (Equations 1 and 2). where: $HPUA$ = Heat per unit area (kJ·m^{-2}); H = Heat yield (kJ·kg^{-1}); W = Weight of available fuel (kg·m^{-2}); R = Rate of spread (m·s^{-1}); I_B = Byram's fireline intensity (kW·m^{-1}·s^{-1}).

The rate of spread was measured with a chronometer to determine the time that the flame front passed from the first line to the end line. The flame length was determined visually with the aid of a graduated wood scale positioned right next to the combustion table and later, confirmed with photographs and videos. The fuel consumption was obtained by weighing the unburned or partially burned fuel load at the end of flaming and smoldering combustion for each experiment.

$$HPUA = H.W \hspace{4cm} [1]$$

$$I_B = H.W.R \hspace{4cm} [2]$$

When the laboratory fires failed to propagate until the end line, their given rate of spread and fireline intensity was zero. The flame length received a zero value only when the fire extinguished before reaching the second line. The fuel consumption and heat per unit area received zero value only when less than 0.5% of the fuel load burned.

Building new models

The new mathematical models to describe the fire behavior were created through multiple regression. The independent variables were selected through the
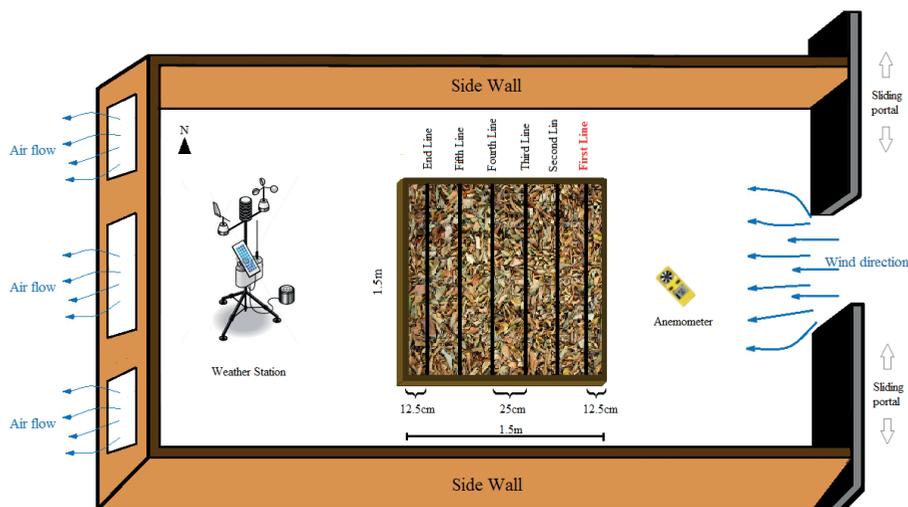
FIGURE 1 Top view layout of the laboratory site and combustion table where the experimental burns where done

analysis of its fit with each dependent fire behavior aspect and/or using the forward stepwise procedure at 5% significance level. All new equations had their coefficient of determination (r^2), p-value coefficient and root mean square error (RMSE) described. The models were developed using the JMP statistical package software (version 7.0, SAS Institute, Cary, NC).

RESULTS

Laboratory burns

The Byram's fireline intensity ranged from 0 to 1,385 with a mean value of 146 kW·m^{-1}. According to McArthur (1967), 348 kW·m^{-1} is the maximum limit for acceptable damage in commercial eucalypt forests. This value was exceeded in 14 of the experiments. The heat per unit area ranged from 0 to 67,334 with a mean value of 16,198 kJ·m^{-2}.

According to the classification of Botelho and Ventura (1990), the rate of spread was in most cases "slow", with a speed less than 1.98 m.min^{-1}. In only three experiments the speed reached the "medium" classification (1.98 – 9.96 m·min^{-1}). The flame length, in most cases, was "short" (< 0.6 m) according to the Roussopoulos and Johnson (1975) classification. The maximum length was 1.2 m. Fuel consumption ranged from 0 to 100%, presenting a mean value of 68% (Table 1).

TABLE 1 Mean, standard deviation, maximum and minimum values for all input and output parameters measured during the 105 experimental fires.

Input Parameter	Mean (Standard Deviation)	Maximum	Minimum
1-h dead dry fuel load (t·ha^{-1})	8.21 (± 2.99)	19.37	1.94
10-h dead dry fuel load (t·ha^{-1})	2.76 (±3.84)	22.72	0
Total dead fuel dry fuel load (t·ha^{-1})	10.97 (±5.16)	33.4	4.5
Fuel bed depth (m)	0.037 (±0.021)	0.118	0.008
Fuel bed bulk density (kg·m^{-3})	35.58 (±17.9)	96.45	13.8
1-h moisture content (%)	17.78 (±7.12)	38.5	7.7
10-h moisture content (%)	16.64 (±4.69)	41.52	8.4
Air temperature (°C)	27.61 (±1.5)	31.7	24.2
Air relative humidity (%)	74.45 (±5.3)	93	59.8
Wind speed (km·h^{-1})	3.66 (±3.7)	15	0

Output Parameter	Mean (Standard Deviation)	Maximum	Minimum
Fireline intensity (kW·m^{-1})	146 (±200)	1385	0
Heat per unit area (kJ·m^{-2})	16,198 (±12,372)	67,334	0
Rate of spread (m·min^{-1})	0.46 (±0.59)	3.13	0
Flame length (m)	0.45 (±0.29)	1.2	0
Fuel consumption (%)	68 (±34.4)	100	0

Creating new models

Based on the analysis of the correlation matrix between all dependent and independent variables (Table 2), new models for the fire rate of spread, flame length and fuel consumption are proposed. All the proposed model plots, with observed versus predicted values, are presented in Figure 2. The variable boundaries for model application are outlined in Table 3.
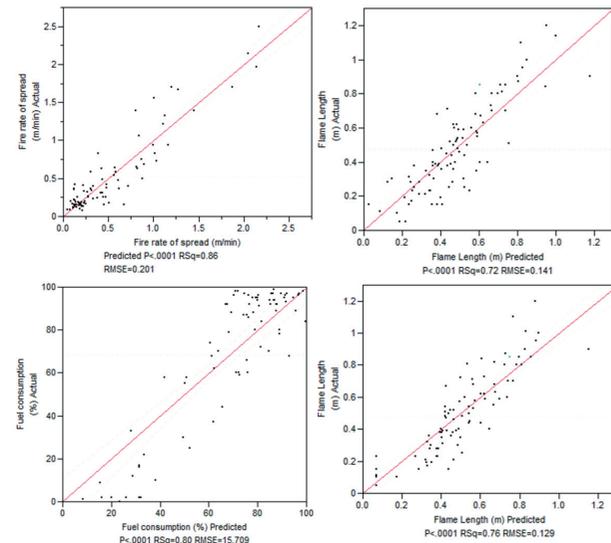
FIGURE 2 Observed (actual) versus predicted (with the proposed models) plots. The red line indicates the line of exact agreement.

Rate of spread model

The proposed model for the fire rate of spread [3] was based on data from 97 experimental burns. Seven burns were not included since the fire did not reach the second line and, therefore, the wind speed was not measured. Data from one other experiment was not used due to discrepant results. According to the forward stepwise procedure, wind speed was the most significant variable for the variation in the rate of spread (p < 0.001), followed by fuel bed bulk density (p < 0.001), and 1-h dead fuel moisture content (p = 0.037). The best fitted model was obtained through nonlinear regression (R^2 = 0.856; p < 0.001), where: R = Fire rate of spread (m·min^{-1}); $U_{1.5}$ = Eye level wind speed (km·h^{-1}); M_{1h} = 1-h dead fuel moisture (%); Bd = Fuel bed bulk density (kg·m^{-3}).

$$R = 39.978 \cdot (U_{1.5} + 0.795)^{0.824} \cdot \exp(-0.09 \cdot M_{1h}) \cdot Bd^{-1.26} \qquad [3]$$

Flame length model

The proposed model for the flame length (Equation 4) was based on data from 95 experimental burns. As in the rate of spread model, seven burns were not included since the fire did not reach the second line and, therefore,

$$FI = 0.402 + 7.52 \cdot Fbd - 0.018 \cdot M_{1h} + 0.027 \cdot U_{1.5} \qquad [4]$$

TABLE 2 Matrix of Pearson correlation coefficients (r) between all inputs and outputs measured during the experimental fires.

	W1h	W10h	WTotal	Fbd	Bd	M1h	M10h	Temp.	RH	U1.5	R	Fl	Fc	Ib
W1h	1.000	0.129	0.676**	0.622**	-0.215*	0.097	0.044	0.020	0.001	0.003	-0.037	0.384**	0.278**	0.247*
W10h	-	1.000	0.819**	0.418**	0.192*	-0.166	-0.160	-0.090	0.018	0.044	-0.157	0.288**	0.007	0.069
WTotal	-	-	1.000	0.671**	0.018	-0.067	-0.093	-0.055	0.014	0.034	-0.138	0.435**	0.166	0.190*
Fbd	-	-	-	1.000	-0.585**	0.051	-0.014	0.053	0.078	0.015	0.117	0.548**	0.259**	0.461**
Bd	-	-	-	-	1.000	-0.137	-0.090	-0.104	-0.042	0.003	-0.152	-0.296**	-0.272**	-0.258*
M1h	-	-	-	-	-	1.000	0.660**	-0.211*	0.266**	-0.110	-0.301**	-0.437**	-0.685**	-0.240*
M10h	-	-	-	-	-	-	1.000	-0.318**	0.225*	-0.074	-0.207*	-0.305**	-0.487**	-0.194*
Temp.	-	-	-	-	-	-	-	1.000	-0.646**	0.133	0.131	0.017	0.207*	0.130
RH	-	-	-	-	-	-	-	-	1.000	-0.139	-0.046	-0.045	-0.207*	0.058
U1.5	-	-	-	-	-	-	-	-	-	1.000	0.651**	0.410**	0.129	0.583**
R	-	-	-	-	-	-	-	-	-	-	1.000	0.510**	0.162	0.826**
Fl	-	-	-	-	-	-	-	-	-	-	-	1.000	0.637**	0.701**
Fc	-	-	-	-	-	-	-	-	-	-	-	-	1.000	0.329**
Ib	-	-	-	-	-	-	-	-	-	-	-	-	-	1.000

W_{1h}: 1-h dead dry fuel load; W10h: 10-h dead dry fuel load; WTotal: Total dead dry fuel load; Fdb: Fuel bed depth; Bd: Fuel bed bulk density; M_{1h}: 1-h fuel moisture content; M10h: 10-h fuel moisture content; Temp.: Air temperature; RH: Air relative humidity; U1.5: Wind speed; R: Rate of spread; Fl: Flame length; Fc: Fuel consumption; * Significant at $p < 0.05$; ** Significant at $p < 0.01$.

TABLE 3 Empirical boundaries of the input variables when using the proposed fire behavior models developed in this study.

Empirical boundaries	$U_{1.5}$ (km·h⁻¹)	Bd (kg·m⁻³)	M_{1h} (%)	Fdb (m)	I_B (kW·m⁻¹·s⁻¹)	W_{1h} (t·ha⁻¹)
Rate of spread model	0 - 15	13.8 – 96.45	7.69 – 38.5	-	-	-
Flame length model	0 - 15	-	7.69 – 38.5	0.008 – 0.120	-	-
Alternative Flame length model	-	-	-	-	0 – 1385.2	-
Fuel consumption model	-	13.8 – 96.45	7.69 – 38.5	-	-	1.94 – 19.37

the wind speed was not measured. Data form three other experiments were not used due to discrepant results. According to the forward stepwise, the variables: fuel bed depth ($p < 0.001$), 1-h dead fuel moisture content ($p < 0.001$) and wind speed ($p < 0.001$), were, in descending order, responsible for the variation in the flame length. The best fitted model was obtained through linear regression ($R^2 = 0.724$; $p < 0.001$), where: *Fl*=Flame length (m); *Fb*=Fuel bed depth (m); M_{1h}=1-h dead fuel moisture (%); $U_{1.5}$=Eye level wind speed (km·h⁻¹).

Alternative flame length model

Since most of the models calculate the flame length from the fire line intensity, an alternative model based on data from 95 experiments (the same used in the original model) was created following this pattern (Equation 5). Nonlinear regression was used to formulate the equation that presented better coefficient of determination than the original model ($R^2 = 0.763$; $p < 0.001$), where: *Fl*=Flame length (m); I_B=Byram's fire line intensity (kW·m⁻¹·s⁻¹).

$$Fl = 0.1 * I_B^{0.35} \qquad [5]$$

Fuel consumption model

The proposed mathematical model for the fuel consumption (Equation 6) was based on data from 100 experimental burns. Five burns were not used due to discrepant results. The 1-h dead fuel moisture was the variable most responsible for the variation in the fuel consumption ($p < 0.001$), followed by fuel bed bulk density ($p < 0.001$) and 1-h dead dry fuel load ($p < 0.001$). The model was built though linear regression ($R^2 = 0.797$; $p < 0.001$), where: *Fc*=Fuel consumption (%); W_{1h}=1-h dead dry fuel load (t·ha⁻¹); *Bd*=Fuel bed bulk density (kg·m⁻³); M_{1h}=1-h dead fuel moisture (%).

$$Fc = 130.402 + 3.317 * W_{1h} - 0.582 * Bd - 3.949 * M_{1h} \qquad [6]$$

DISCUSSION

Overall, most of the experimental burns propagated slowly and with short flame. The fuel consumption, important data mainly for use in prescribed fires (BROWN et al., 1985; FERNANDES; LOUREIRO, 2013), presented a mean value of 68%.

The principal explanation for the low rate of spread and short flame length was the high moisture content of the fuel load that presented a mean value of approximately 17%. This high value was directly related to the atmospheric conditions during the fuel collection procedure and experimental burns. The air relative humidity, one of the main factors that influences the fuel

moisture content (MCARTHUR, 1962; MCARTHUR, 1967; VAN WAGNER, 1974; DEEMING et al., 1977; ROTHERMEL et al., 1986), presented a mean value of 74.45% during the experimental fires and was significantly correlated with the fuel moisture content for the 1-h and 10-h dead fuel class (Table 2).

Although the meteorological parameters in the laboratory were similar to those described in the field (WHITE et al., 2013), extreme dryness and high wind speed conditions were not analyzed. For this reason, the applications of the proposed models are limited by empirical boundaries as described in Table 3.

The mathematical models proposed in this study where formulated to be both simple (easy to use, with a minimum of independent variables) and efficient. The *"Eucalyptus Fire Safety System"*, an open source Delphi-based software, was created based on these equations.

The variables used in the proposed fire rate of spread model follow the pattern of others in literature. Wind speed and fuel moisture, directly or indirectly determined through meteorological data, are the most common input variables. Both are used in the Rothermel (1972) surface fire spread model and in others, such as: Mendes-Lopes et al. (2003) and Fernandes (2009) for fire in *Pinus pinaster* litter in Europe; Forestry Canada Fire Danger Rating Group (1992) for Canadian forests; McArthur (1967), Gould et al. (2007) and Cheney et al. (2012) for eucalyptus forests in Australia; and Fernandes (2001) for shrub vegetation in Portugal. In all the models mentioned above, the wind speed positively influences the rate of spread while the moisture negatively. The degree of influence of each variable changes from case to case.

Fuel characteristics, such as bed depth and load, are also commonly used as input in existing fire rate of spread models (e.g. ROTHERMEL, 1972; FERNANDES, 2001; AZAKA et al., 2012). Alternatively, models such as Gould et al. (2007) and Cheney et al. (2012) instead of using these variables as input, use a fuel hazard score that represents a subjective assessment of the flammability based on the fuel load, bed depth, density, continuity, type of bark and morphological development of the vegetation (CHENEY et al., 2012). Even though the use of the fuel bed bulk density as a direct input variable is not common, it is accepted that fire spreads faster in a less dense fuel bed (ANDERSON, 1969; ROTHERMEL, 1972; SOARES, 1979; MORVAN; DUPUY, 2001).

The existing models that describe flame length usually use fireline intensity or fire rate of spread to predict it. The Byram (1959) model, one of the most used and cited, estimates flame length based on fireline intensity, which in turn, is calculated from fire rate of

spread, available fuel load and fuel heat content. The models of Thomas (1963) and Dupuy et al. (2011), also calculate flame length based on fireline intensity. Fernandes (2009), through experimental burns in forests of *Pinus pinaster* in Portugal, formulated a model to describe flame length using fire rate of spread and fuel moisture content. The Gould et al. (2007) and the Cheney et al. (2012) models, developed from burns in dry eucalyptus forests in Australia, use fire rate of spread and the elevated fuel height to calculate flame height.

The initial purpose of this study was to build fire behavior models based only on easily obtained independent variables, therefore the proposed flame length model is based on the fuel bed depth, 1-h fuel moisture and wind speed. However, since a high correlation between flame length and fireline intensity (a dependent variable) was verified, an alternative model was also developed using it as input. The alternative model presented better coefficient of determination than the original model.

Concerning fire fuel consumption, the proposed model was built using the fuel moisture, 1-h dead fuel load and bed bulk density as input variables. High moisture content reduces the thermal efficiency, since heat is expended to evaporate the water. Consequently, less energy is available for the combustion reaction. In fuels with moisture content above 25%, generally the fire does not spread, or spreads only sporadically (ALBINI, 1979; NELSON, 2001; SOARES; BATISTA, 2007). The negative influence of fuel moisture in fire consumption has already been described and modeled by several authors, only changing the degree of influence from case to case (e.g. BROWN et al., 1985; BROWN et al., 1991; HARRINGTON, 1987; FERNANDES; LOUREIRO, 2013).

No publications using the fuel bed bulk density to estimate the fuel consumption were found. Nevertheless, Harrington (1987) modeled the fuel consumption using as input the fuel moisture content and the fuel bed depth in a linear regression model. Since fuel bed depth is inversely proportional to fuel bed bulk density, the higher the fuel bed bulk density the smaller the fuel consumption.

In the experimental burns, only the fuel load from the 1-h class had significant correlation with fuel consumption. This happened because in the experiments with low 1-h load, sometimes the fire extinguished without burning all the fuel on the combustion table. Since fuels with lower surface-area-to-volume rate are more difficult to ignite (ROTHERMEL, 1972; SOARES; BATISTA, 2007), the 10-h and the total dead dry fuel load classes showed no significant correlation with the fuel consumption. Only in some of the experiments with

a high fireline intensity, did the entire fuel load, including the 10-h class, burn.

The 10-h class presented a significant correlation with the fuel bed bulk density, which was to be expected since these fuels present a low surface-area-to-volume ratio (SAV). As the fuel density negatively affects fuel consumption, the 10-h dead fuel load has the same effect, particularly in low intensity fires.

While there exist some mathematical models for estimating post fire fuel consumption (e.g. HARRINGTON, 1987; BOTELHO et al., 1994; CALL; ALBINI, 1997; FERNANDES; LOUREIRO, 2013), they were not evaluated in this nor in the previous study (WHITE et al., 2017) since they are specific for some environmental parameters and not commonly used.

The models proposed in this study presented good statistical parameters, however there are some limitations. First, they were based solely on laboratorial fires with a head fire width of 1.5 m and have not been evaluated for larger wild fires. Second, they were designed for commercial eucalyptus plantations without an active understory, predicting fire behavior specifically in eucalypt litter. Third, all the experimental fires were done in level ground, therefore additional calculations are required for slope consideration. Fourth, they present empirical boundaries for all input variables as showed in Table 3.

Also, it is important to mention that even though models for estimating fire behavior are used by fire services, especially in the United States, Canada and Australia, it is clear that they are auxiliary tools. Decisions should not be taken based solely on simulations, as discrepancies between simulated and experimental data are commonly found in published works (e.g. GOULD et al., 1996; BURROWS, 1994; BURROWS, 1999; CRUZ; FERNANDES, 2008; MCCAW et al., 2008; STEPHENS et al., 2008; FERNANDES, 2009).

Since forest fires are highly influenced by variations in atmospheric conditions, it is essential that those who are coordinating the suppression activities know how to react. Sudden changes in speed and direction of wind, for example, are the leading causes of accidents during suppression operations. Therefore, the operational use of mathematical models to predict fire behavior should be done carefully and preferably by people experienced in fire management.

Given that the models proposed in this study were based solely in laboratory fires with a short line of ignition and have not yet been tested/adjusted in the field, it is recommended for use only in studies and experimental activities.

CONCLUSIONS

Overall, most of the laboratory experiments presented a low fireline intensity, heat per unit area, rate of spread and flame length. The fireline intensity presented a mean value of 146 $kW.m^{-1}$.

The fire rate of spread proposed model is based on wind speed, fuel bed bulk density and 1-h dead fuel moisture content ($r^2 = 0.86$). The flame length model is based on fuel bed depth, 1-h dead fuel moisture content and wind speed ($r^2 = 0.72$). The fuel consumption proposed model has as independent variables: 1-h dead fuel moisture, fuel bed bulk density and 1-h dead dry fuel load ($r^2 = 0.80$).

The use of the proposed models and of the software *Eucalyptus Fire Safety System* are limited by empirical boundaries. Before they can be used in operational activities, it is necessary new studies to verify their efficiency in the field.

ACKNOWLEDGMENT

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