Correlation analysis and fuel moisture estimation based on FMA and FMA⁺ fire danger indices in a *Pinus elliottii* plantation in southern Brazil

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Abstract

This research was carried out in a *Pinus elliottii* plantation, established in 1984, with 47.16 m².ha⁻¹ of basal area, located in the Rio Negro Forest Research Station, owned by the Paraná Federal University, Paraná State, southern Brazil. The research objectives were to analyze the correlations between the FMA and FMA⁺ fire danger indices and the fine fuel moisture, and develop mathematical models to estimate the fuel moisture based on those indices. The meteorological variables were obtained from the SIMEPAR weather station, located 50km away, and from a pluviograph and a thermo-hygrograph installed in the study area. The dead forest fuels were collected from 30x30cm plots, between 12 noon and 2:00PM, and classified as: AA – surface layer; AB – intermediate layer; AC – lower layer; and B – woody material with 0.7 to 2.5cm diameter. The average fuel layer thickness ranged from 14.8 to 15.3cm. The total fuel load varied from 3185.50 to 4266.01g.m⁻². The fire danger indices were calculated daily and the values obtained on the fuel collecting days were used to calculate the correlations. The correlation coefficients between relative humidity and fuel classes were 0.42, 0.36, 0.32, and 0.41 for the AA, AB, AC, and B classes, respectively. The correlation coefficients between precipitation and fuel classes were 0.57, 0.38, 0.34, and 0.15 for the AA, AB, AC, and B classes, respectively. Higher correlation coefficients were obtained between fuel moisture and fire danger indices. The correlation coefficients between the fuel classes and the FMA⁺ were -0.53, -0.56, -0.63, and 0.81 for the classes B, AB, AA, and AC,

respectively. The FMA^+ was the most efficient variable in the modeling development to estimate dead fuel moisture.

Keywords: Pinus elliottii, fire danger indices, forest fuel, forest protection.

1 Introduction

Pinus sp plantations represent approximately 35% of the Brazilian afforested areas, and the State of Paraná, with 37% of the total, ranks first in relation to the total area planted with pine in Brazil [1]. The crescent expansion of the afforested areas, mainly in the country's southern region, requires a continuous improvement in management and protection techniques. Forest fires are a constant threat to the plantations and represent one of the main objectives of the protection plans.

Fuel moisture knowledge is essential to estimate some fire behavior parameters, such as fire intensity and rate of spread, and is an important factor in prescribing a successful controlled burning. Fuel moisture is also important to appraise the forest fire danger [2, 3].

In Brazil the fuel moisture estimation has been done through direct field sampling and laboratory processing. The field samples are weighed (humid mass) and taken to the laboratory to dry until they have reached constant weight, and then, weighed again (dry mass). The relationship between humid and dry masses gives the moisture content of the collected sample.

According to Batista [4], indirect methods could facilitate the fuel moisture content determination, making the work of the technicians responsible for forest protection activities easier. Therefore, correlation analysis between fire danger indices (FMA and FMA^+) and fuel moisture content could become an important tool in forest prevention and suppression actions.

The objectives of this work were to analyze the correlations between the FMA and FMA^+ fire danger indices and the fine forest fuel moisture, and to develop mathematical models to estimate the fuel moisture based on those indices.

2 Methods

2.1 Location

The research was developed in the Rio Negro Experimental Station (Figure 1), owned by the Federal University of Paraná and administrated by the Forest Science Department, located in the south of the Paraná State, approximately 26°04' S latitude and 49°45'W longitude. The mean altitude of the area is 793m above sea level, the annual precipitation is around 1,400mm, and the climate is Cfb, according Koppen classification, with the mean temperature of the hottest month below 22°C, no dry season (driest month with precipitation > 60mm), and more than 10 frosts a year.

Figure 1: Study area location.

2.2 Meteorological data

According to Brown and Davis [5], the main variables to control the fuel moisture are precipitation, relative humidity, and air temperature. Wind and solar radiation are also important but act indirectly through the fuel temperature modification, the air temperature, and the fuel adjacent thin air layer.

The meteorological data used in this study were obtained from a meteorological station that belongs to the Paraná State official network (Paraná Meteorological System – SIMEPAR), located approximately 50 km from the

Research Station, and also from a pluviograph and a thermo-hygrograph installed in the experiment area.

2.2.1 Sampling and statistical analysis

Site selection for installing the experiment was done after observing the whole stand, looking for a representative area and avoiding the edges. Sampling collection was programmed to extend for a full year, to include the four seasons. It started in the winter of 2007 and ended in the autumn of 2008, always sampling in the driest periods of each season.

The experimental area totaled 200 m^2 , divided in four sampling strips, corresponding to the year seasons (Figure 2). The strips were located between the trees lines, in the north-south direction, and the material was collected in the spaces between the trees. Eight samples were collect per day, always between 12 noon and 2:00 PM, during 60 days (15 days per season), totalizing 480 samples. The sampling units measure $30\times30\text{ cm}$. The collected fuel was classified according to Brown et al. [6], using a diameter gauge.

The collected material was divided in two classes: A – needles and small branches with diameter $< 0.7\text{ cm}$; and B – woody material (small branches in different decomposition stages) with diameter between 0.71 and 2.5 cm . Woody material with diameter $> 2.5\text{ cm}$ was not sampled due to the high variability and because they take much time to change the moisture content (high timelag).

According to Molchanov [7] the duff layer (decaying leaves and small branches) gets a special structure due to the influence of precipitation, air temperature, cryptogammic flora, and insects, forming three different strata. Therefore, the A class was subdivided into three sub-classes (Figure 3), as follows:

Figure 2: Sampling strips and units.

FUEL LAYERS CLASSIFICATION

Figure 3: Characterization of the fuel layer, showing the B class and the A sub-classes.

- Surface layer (AA) – composed of needles and small branches (diameter > 0.7 cm); characterized by needles of clear brown color, bright, quite rigid, recently felled.
- Intermediate layer (AB) – also composed of needles and small branches but the needles presented a brown color, bright less, less rigid, indicating the decomposition process beginning.
- Lower layer (AC) – also composed of needles and small branches but the needles presented a dark brown color, low rigidity, and advanced decomposition process.

In the laboratory, the collected fuel was transferred to paper bags and placed in an oven to dry, at 75°C, during 72 hours. After that, the moisture content was determined through the following equation:

$$MC = \frac{P_u - P_s}{P_s} 100$$

where:

MC = moisture content in %;

P_u = fuel humid weigh (Just after collected in the field);

P_s = fuel dry weight (after oven dried).

Initially, a correlation analysis including all variables was performed. The mathematical models used to estimate the fuels moisture content were obtained through the backward process, which uses the variables selected by the correlation analysis. To select the best models, two comparing tests were used:

- a) Determination coefficient (R^2) – parameter that expresses how much of the dependent variable is explained by the independent variables.

- b) Estimation standard error (S_{yx}) – that expresses how much, in average, the observed values varies in relation to the estimated values.

To interpret the variables included in the fuels moisture content mathematical models and in the correlation matrices, the following conventions were adopted (Table 1).

To develop the equations for estimating the fuel moisture content numeric values were used to identify the seasons of the year, as follows:

- a) 1 – winter
- b) 2 – spring
- c) 3 – summer
- d) 4 – autumn

The forest fire danger indices (FMA and FMA^+) were calculated through a Pascal language program [8], according to the equations developed by Soares [9] and Nunes [8]:

$$FMA = \sum 100 \frac{1}{UR}$$

Table 1: Description of the variables used in the correlation analysis and the mathematical models.

Variables initials	Variables description	Units
E	Season of the year	1 to 4
U_{AA}	Moisture content of the surface fuel (AA)	%
U_{AB}	Moisture content of the intermediate fuel (AB)	%
U_{AC}	Moisture content of the lower fuel (AC)	%
U_B	Moisture content of the woody fuel (B)	%
U_{FZ}	Relative humidity at 1;00PM	%
W_{Lp}	Wind speed (SIMEPAR weather station)	$M.s^{-1}$
P_{FZ}	Precipitation	mm
F_{Fz}	Monte Alegre formula (FMA)	Value
GF_{Fz}	FMA danger degree	1 to 5
F^+_{Fz}	Enhanced Monte Alegre formula (FMA^+)	Value
GF^+_{Fz}	FMA^+ danger degree	1 to 5

where:

FMA = Monte Alegre Formula

UR = Relative humidity at 1:00 PM

$$FMA^+ = \sum 100 \left(\frac{1}{UR} \right)^v$$

where:

FMA^+ = Enhanced Monte Alegre formula

UR = Relative humidity at 1:00 PM

v = wind speed in $m.s^{-1}$ at 1:00 PM

For the correlation analysis and the fuel moisture content estimation mathematical models, the indices were included according to the daily values and the danger degree scale (Table 2).

3 Results and discussion

The matrix presented in table 3 shows the correlation coefficients among the fire danger indices, the meteorological variables, and the fuels moisture contents. The danger degree levels (1 to 5) presented better results when compared to the daily indices values. The enhanced Monte Alegre Formula (FMA^+) presented higher correlation with the fuel moisture than the original FMA, demonstrating that the wind speed inclusion in the original equation improved its performance regarding the correlation with the fuel moisture. It can be observed in table 3 that the correlation coefficients between the danger degree of the FMA^+ and the fuel moisture of classes AA, AB, AC, and B were -0.63, -0.56, -0.81 and -0.53, respectively, whereas for the FMA the coefficients were -0.60, -0.47, -0.71 and -0.36. The coefficients were negatives because as higher is the fire danger, lower is the fuel moisture. The AC class presented higher association ($r = -0.81$), probably because it is not subject to fast moisture loss or gain, due to its position in the fuel layer.

Table 2: Fire danger degrees of FMA and FMA^+ used in the correlation analysis and the fuel moisture mathematical models.

Danger degree	Numeric value
Null	1
Small	2
Medium	3
High	4
Very high	5

Table 3: Correlation matrix of the fuel classes moisture in function of the meteorological variables and the fire danger indices.

	U _{AA}	U _{AB}	U _{AC}	U _B	U _{Fz}	W _{Lp}	P _{Fz}	F _{Fz}	GF _{Fz}	F ⁺ _{Fz}
U _{AA}										
U _{AB}	0.67**									
U _{AC}	0.57**	0.59**								
U _B	0.61**	0.68**	0.65**							
U _{Fz}	0.42*	0.36*	0.32*	0.41*						
W _{Lp}	0.04	0.16	-0.19	-0.06	-0.17					
P _{Fz}	0.57**	0.38*	0.34*	0.15	0.19	0.28				
F _{Fz}	-0.46**	-0.46**	-0.80**	-0.49**	-0.34*	0.28	-0.34*			
GF _{Fz}	-0.60**	-0.47**	-0.71**	-0.36*	-0.25	0.05	-0.71**	0.74**		
F ⁺ _{Fz}	-0.46**	-0.46**	-0.80**	-0.49**	-0.34*	0.28	-0.34*	1.00	0.74**	
GF ⁺ _{Fz}	-0.63**	-0.56**	-0.81**	-0.53**	-0.32*	0.12	-0.57**	0.74**	0.93**	0.86**

The B class presented lower association with the FMA^+ , perhaps because the timelag depends on the fuel layer thickness or the size of the fuel particles. According to Fosberg and Deeming [10], fuel particles with 0.7 to 2.5 cm diameter (class B) present a 10 hour timelag in the average, against 1 hour average for fuel particles smaller than 0.7 cm.

The correlation coefficients between the fire danger indices (FMA and FMA^+) and the fuel moisture presented better results when compared to the coefficients obtained between the fuel moisture and the meteorological variables, namely relative humidity and precipitation (Table 3).

The models used to estimate the fuels moisture contents, presented in Table 4, were based in the meteorological variables (relative humidity, precipitation, and wind speed) and the fire danger indices (FMA and FMA^+). In the winter, the best estimation was observed in the AA fuel class ($R^2 = 0.59$), using a single

Table 4: Selected mathematical models to estimate fuel moisture content in a pine plantation, in the Rio Negro Experimental Forest, Paraná, Brazil.

Season	Fuel class	R^2	Model
Winter	AA	0.59	$U_A = 311.672 - 55.309 GF + F_Z$
	B	0.28	$U_B = 88.875 + 1.609 U_{F_Z}$
Spring	AA	0.64	$U_A = -41.0643 + 1.5111 U_{F_Z} + 1.7216 P_{F_Z}$
	AB	0.76	$U_{AB} = 184.5024 + 1.4545 U_{F_Z} - 8.0303 F + F_Z$
	AC	0.79	$U_{AC} = 250.5632 + 0.9582 U_{F_Z} - 4.8418 F + F_Z$
	B	0.33	$U_B = 230.3618 - 19.2836 GF + F_Z$
Summer	AA	0.85	$U_A = 97.79 + 0.69 U_{F_Z} + 2.83 P_{F_Z} - 25.55 GF + F_Z$
	AB	0.73	$U_{AB} = 227.14 - 10.41 P_{F_Z} + 33.54 GF + F_Z$
	AC	0.66	$U_{AC} = 335.64 - 32.10 GF + F_Z$
	B	0.60	$U_B = 311.871 - 3.155 P_{L_p} - 34.019 GF + F_Z$
Autumn	AA	0.82	$U_A = 87.94 + 0.04 U_{F_Z} + 1.40 P_{F_Z} - 1.25 F + F_Z + 2.04 GF + F_Z$
	AB	0.85	$U_{AB} = 293.11 + -0.30 U_{F_Z} - 0.59 P_{F_Z} - 3.03 F + F_Z$
	AC	0.83	$U_{AC} = 424.66 - 5.85 P_{F_Z} - 46.86 GF + F_Z$
	B	0.82	$U_B = 185.62 + 1.18 U_{F_Z} - 3.66 P_{F_Z} - 3.31 F + F_Z + 10.57 GF + F_Z$

variable (GF^+_{FZ}). For the B fuel class the best fit was very poor ($R^2 = 0.28$), and for the fuel classes AB and AC, none of the tested models presented reliable estimations.

In the spring, the best estimations were observed for the AB and AC fuel classes, with R^2 equal to 0.76 and 0.79, respectively. In both cases the variables included in the models were U and F^+ . The best model for the AA fuel class was obtained through the U and P variables ($R^2 = 0.64$). For the B class the best fit was obtained with the GF variable, but as observed in the winter, the association was very poor ($R^2 = 0.33$).

In the summer, the models selected to estimate the moisture content of all fuel classes presented good fits, with determination coefficients ranging from 0.60 to 0.85. It must be emphasized that the variable GF^+ was selected to compose all the models.

For the autumn, the selected models presented the highest determination coefficients, $R^2 = 0.82, 0.83, 0.85$, and 0.82 for the fuel classes AA, AB, AC, and B, respectively. Generally, the independent variable fire danger index FMA^+ presented better estimations for most of fuel classes, especially in the autumn.

4 Conclusions

The fire danger indices, FMA and FMA^+ , presented higher correlation coefficients with the fuel moisture than the isolated meteorological variables.

The FMA^+ presented better results than the FMA and was the most important variable in the fuel moisture content estimation.

Significant meteorological differences between the seasons were observed; therefore, the models developed for each season presented better fits.

The fuels inside the stands presented high moisture content, even when the indices indicated high and very high fire danger.

The use of the FMA^+ to estimate the fuels moisture content produced fast, efficient, and reliable information.

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