New Empirical Model to Estimate Fine Dead Fuel Moisture Content Under Equatorial Climate Conditions.

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Introduction

The fuel moisture content (FMC) represents the amount of water present in the plant biomass expressed as a percentage of its dry fuel weight. The higher the FMC, the greater the difficulty for the fuel to burn, since a high amount of energy will be necessary to evaporate all the water and then, initiate the combustion process (Nelson, 1984; Matthews, 2014; White 2018).

While the moisture content of live fuels depends mainly on the physiological characteristics of the plants, the moisture content of dead fuels is affected by their size and by local atmospheric conditions, such as air temperature, humidity, wind speed, solar radiation, rainfall (Britton, 1973; Matthews, 2014). In the absence of rainfall, the dead FMC will depend only on the exchange of water vapor between the fuel and the environment (adsorption and desorption). In a situation when the temperature and humidity remain constant, the dead fuel tends to reach the equilibrium moisture content, in other words, there is no net exchange of moisture between environment and fuel (Britton, 1973; Nelson, 1984). However, this condition can only be reached in a laboratory with controlled climate, since in nature, temperature and humidity vary uninterruptedly throughout the day (Nelson, 1984).

One hour timelag dead fuels (timelag refer to the amount of time it takes a dead fuel particle to reach about 63% of the difference between its current moisture content and the equilibrium moisture content) include dead needles, leaves, herbaceous plants and fine stems generally found in the litter layer. The moisture content of these fuels can change rapidly with rainfall or changes in atmospheric conditions. Pieces of fuel with a larger diameter (10-h, 100-h and 1000-h timelag fuels), on the other hand, generally respond more slowly to changes in environmental conditions. The greater the fuel diameter the slower the moisture content will change (Lancaster, 1970; Matthews, 2014).

The moisture content of the dead fine fuel load (1-h timelag) is recognized as a key parameter that influences the fire ignition and behavior (Gisborne, 1928; White, 2018). The real-time knowledge of the dead 1-h FMC is essential to determine how the fire will behave: rate of spread, flame length, fire line intensity and other characteristics, since wildfires usually begin and propagate in the dead and fine fuel load that composes the forest litter (Rothermel, 1972). Therefore, efficient preventive actions, such as prescribed burns and firefighting activities will more likely be successful if the dead 1-hr FMC is known (Fosberg *et al*., 1970).

Despite relationships between weather and dead fuel moisture content have been studied for over a century, reliable methods to predict the variation of the FMC have not yet been developed (Nelson. 2000; White 2018). Various approaches and models were developed over the years, however, they usually have restricted application, being unable to predict with efficiency in situations where the climate and the vegetation characteristics are different from the environments where they were developed (White, 2018). Among several existing models currently in use to estimate the fine dead FMC and, consequently, the wildfire risk, the Canadian Forest Weather Index (FWI) (Van Wagner, 1974) stands out, since it is the most used on the planet (Bianchi and Defosse, 2014; White 2018).

This study had as objective to assess the efficiency of the FWI in determining the dead fine FMC and to develop a new model capable of better predicting the dead fine FMC at the study area.

Methods

All the procedures necessary for the development of this study were carried out in the municipality of Itabaiana (10°41’06”S e 37°25’30”O), located in the Northeast region of Brazil in the state of Sergipe. The climate, by the updated classification of Köppen and Geiger, is Equatorial savannah with dry summer (As) (Kottek *et al*. 2006), with mean annual rainfall of 1200 mm.

The fine dead fuel load was collected in an open area dominated by grasses and scattered trees. Therefore, it was composed mainly from dead/cured grasses and dead leaves. In the area where the fuel was collected, a DAVIS Vantage Vue weather station (K6250 model) was installed at 1.8 meters high and programed to measure weather parameters every 10 minutes.

Initially, the fine fuel load was collected, packed in paper bags and immediately had their fresh weight determined with a scale with precision of 0.1 g. In total, 861 samples were weighted, each of which with about 100 g of wet fuel load. The sampling procedure lasted for two years and was done during day and night periods. After the fuel samples had their fresh weight determined, they were taken to laboratory to dry in an oven at 100ºC until they reach constant weight (approximately 24h) and had their dry weight and moisture content determined. The FMC was then correlated with the weather parameters measured by the weather station at the time where the fuel samples were collected. The weather parameters measured in this study were: air temperature, air relative humidity, wind speed, rainfall in the last 24 hours and days since the last rainfall. The nominal dependent variable (fine dead FMC) was modeled using the forward stepwise procedure to select which of the weather parameters better explained its variation.

The fine dead FMC according the FWI was determined for each sample using the FWI Calculator version 10.4.1.107. Since the calculator only computes the FWI fine fuel moisture code (FFMC), it was necessary to convert the code into the fine dead FMC (Equation 1).

$$m = 101 - FFMC \qquad \text{(Equation 1)}$$

Where: m = fine dead moisture content; $FFMC$ = Fine fuel moisture code.

The efficiency of the FWI in determining the fine dead FMC was evaluated through the analysis of variance (ANOVA) between real and estimated values. The efficiency of the regression models built in this study were assessed through the coefficient of determination (r^2), the p-value coefficient and the root mean square error (RMSE). All statistical analysis were performed using the software JMP version 7.0. The significance level was set at $\alpha = 0.05\%$.

Results

Based on the analysis of the 861 samples, the fine dead FMC ranged from 1.8% to 75.2% with a mean value of 17.5%. According the measurements took during the sampling procedure, the air temperature ranged from 20.3 ºC to 38.7 ºC with a mean value of 27.5 ºC, the air humidity from 25.8% to 99% with a mean value of 71.4%, the rainfall amount in the last 24 hours ranged from 0 to 75 mm, presenting a mean value of 2,3 mm. The number of days without rainfall ranged from 0 to 33, the mean was 4 days. The wind speed fluctuate from 0 to 24.5 km h^{-1}, with a mean value of 2.8 km h^{-1}. The fine dead FMC calculated using the FWI ranged from 6,6% to 96,1%, presenting a mean value of 25,5% (Table 1).

Table 1 – List of minimum, maximum and mean values of all variables used in this study.

Parameter	Minimum	Maximum	Mean
Measured Fine Dead FMC	1.8%	75.2%	17.5%
Estimated Fine Dead FMC (FWI)	6,6%	96,1%	25,5%
Air Temperature	20.3 ºC	38.7 ºC	27.5 ºC
Air Humidity	25.8%	99%	71.4%
Rainfall in the last 24 hours	0 mm	75 mm	2.3 mm
Wind Speed	0 km h^{-1}	24.5 km h^{-1}	2.8 km h^{-1}
Days without rainfall	0	33	4

The fine dead FMC estimated by the FWI was overestimated in most cases. Its mean value was 8% higher than the measured fine dead FMC. According ANOVA test, the estimated FMC was statistically different from the real FMC ($F = 102.53$; $p < 0.001$). Since both variables presented a significant correlation ($r = 0.79$; $p < 0.001$), it was possible to build an adjustment model using linear regression ($r^2 = 0.63$; $p < 0.001$; RMSE = 7.85) (Equation 2).

$$m_{real} = 2.67 + 0.57 * m_{estimated} \qquad \text{(Equation 2)}$$

Where: m_{real} – Measured fine dead FMC

$m_{estimatade}$ – Estimated fine dead FMC using the FWI

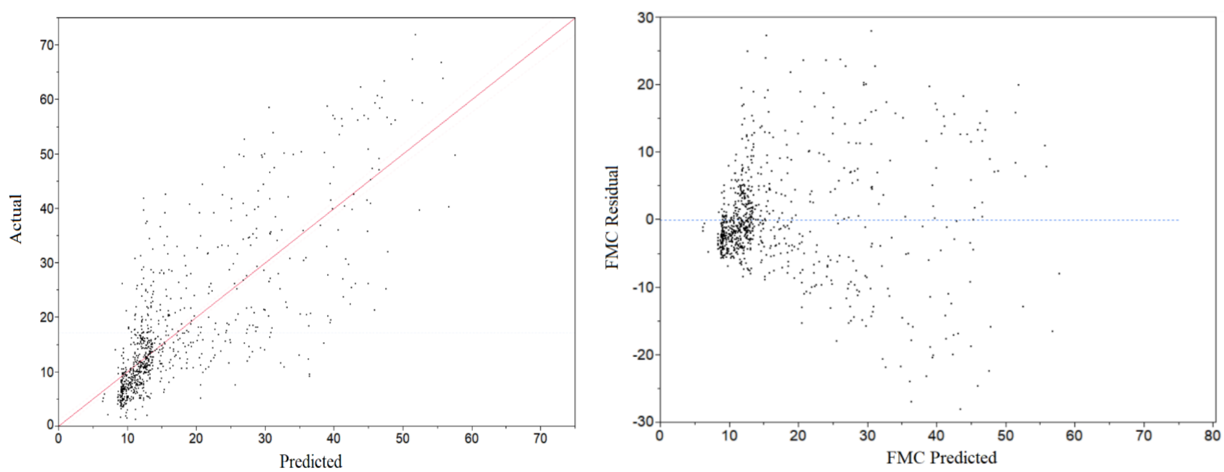

Figure 1 – Observed fine dead FMC (Actual) versus predicted (using the FWI) plot on the left side. On the right, plot of residuals versus predicted response.

Seeking to better predict the fine dead FMC at the study site, a new multivariate regression model was created. Using the forward stepwise procedure, air relative humidity was the most significant variable responsible for the variation of the fine dead FMC ($p < 0.001$), followed by the rainfall amount in the last 24 hours ($p < 0.001$) and by the number of days without rainfall ($p < 0.001$). The inclusion of the variables air temperature ($p = 0.09$) and windspeed ($p = 0.12$) did not result in a significant improvement of the model efficiency, therefore, both variables were not included. The best fitted model was obtained through nonlinear regression ($r^2 = 0.76$; $p < 0.001$; RMSE = 6.8) (Equation 2). The proposed model presented a better coefficient of determination and lower error than the FWI adjustment model (Figure 2).

$$FDFMC = e^{1.54319+0.00022*H^2+0.13659*\sqrt{R_{24h}}-0.13032*NDWR} \qquad \text{(Equation 3)}$$

Where: *FDFMC* – Fine dead fuel moisture content (%); *e* - Base of the natural logarithm = 2.71828; *H* – Air relative humidity (%); R_{24h} – Rainfall amount in the last 24 hours (mm); *NDWR* – Number of days without rainfall.

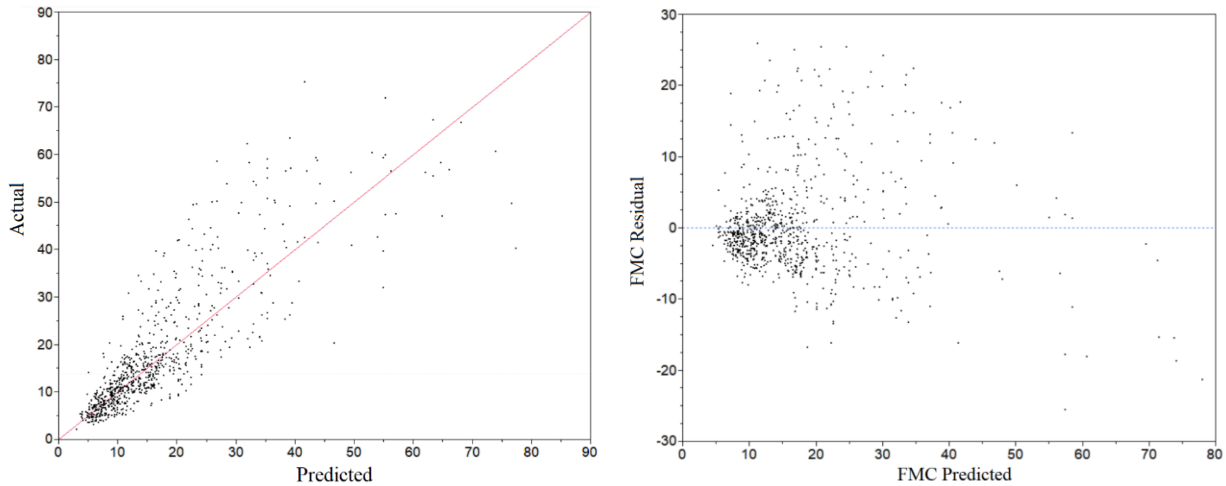

Figure 2 – On the left side, plot of observed fine dead FMC (Actual) versus predicted (using the proposed model). On the right, plot of residuals versus predicted response.

Discussion

The FWI is a set of mathematical equations that is used as a fire danger rating system. It was created in Canada based on dozens of experimental fieldworks conducted between 1928 and 1970 in natural pine forests (Van Wagner, 1974). It is the most tested and used model in the world and usually presents good results. The FWI has already been tested and had its efficiency proven in Argentina (Bianchi and Defosse, 2014), China (Li *et al*., 2014; Zhang *et al*., 2014), Portugal (Rainha *et al*., 2002), Russia (Mcrae *et al*., 2009), Spain (Gabban *et al*., 2008), Northern Europe (Tanskanen *et al*., 2005), Mediterranean Europe (Viegas *et al*., 1999; Good *et al*., 2008), Germany (Holsten *et al*. 2013), United States (Roads *et al*., 2001), Indonesia and Malaysia (De Groot *et al*., 2007). However, publications that report inaccuracy of the FWI index are also common. In a study in Slovenia, for example, Sturm *et al*. (2012) concluded that the results obtained with the original FWI were not satisfactory; Viegas *et al*. (2004) and Alexander (2008) found that a FWI hazard class calibration was required for all 18 districts in Portugal and in New Zealand, respectively, for the effective use of the model; Camia and Amatulli (2010) have suggested the implementation of local fire data in the FWI for better system functionality at the European level. In a single study carried out in Brazil, Cerapiá (2006) concluded that the FWI presented a low correlation with recorded fires outbreaks.

The results found in this work concluded that the FWI overestimated de real fine dead FMC in approximately 8%, however, both variable presented a high and significant correlation, therefore it was possible to build a statistically significant model of adjustment. The differences between real and estimated values can be justified due to differences in vegetation and climate aspects between temperate regions with predominance of pine forests (characteristics where the experiments to build the FWI were done) and equatorial climate regions with vegetation ranging from tropical forests to open areas dominated by grasses. Such conclusion is based on the fact that the physical process of fuel moisture absorption or desorption depend on fuel characteristics such as surface area to volume ratio and weather conditions (Britton *et al*., 1973; Nelson, 1984). Also, empirical models such as the FWI that are built based on experimental observations, generally have their use restricted to areas with similar characteristics from where the experiments were conducted (White, 2018). It is always recommended to evaluate the efficiency of fire risk or fire behavior models before using them operationally in a certain region, especially if the climate and vegetation characteristics are different from which the models were developed (White *et al*., 2016).

Despite the existence of dozens of mathematical models built to estimate the fuel moisture content of dead fuels (Matthews, 2014), only one model was found in the literature that was developed using empirical data of FMC measured in a Brazilian equatorial climate region (Ray *et al*., 2010). Nevertheless, the model was built to estimate the FMC of the Amazon rainforest litter. In addition to using the number of days without rainfall, the air temperature and relative humidity (in the form of the vapor pressure deficit), the respective model uses the foliar area index of the forest as an input variable. Therefore its use for areas without tree cover is impractical.

The new model developed uses three variables (air humidity, rainfall amount and days without rainfall) that have already been proved to have a substantial effect on the fine dead FMC (Van Wagner, 1974; Ray *et al*., 2010; White *et al*., 2016). Despite several authors consider that the processes involving rainfall are too complex for modelling the FMC (Viney 1991; Matthews *et al*., 2010), the built model presented good statistical parameters. It differs from other models that are commonly used to determine the fire danger and/or the FMC, for being capable to be used at any hour of the day and for it simplicity. Any person that has access to a weather station with a pluviometer and a hygrometer can use the model.

New studies should be done in order to verify the efficiency of this new model for the study area and for other locations. If its efficiency is proven, the model can be used as a fire danger index, since the FMC of the fine dead fuel is directly related to the fuel ignition and fire behavior. Also, it can be used as a tool for defining the ideal conditions to perform prescribed/control burns.

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