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FIRE BEHAVIOR MODELING IN HERBACEOUS VEGETATION IN THE BRAZILIAN CERRADO

Ronie Silva Juvanol[1*], Jenival Silva Farias Junior[2], Nilton Cesar Fiedler[3], Priscila Alves Barroso[1]

[1*]Universidade Federal do Piauí, Campus Professora Cinobelina Elvas, Bom Jesus, Piauí, Brasil – roniejuvanhol@ufpi.edu.br; pa.barroso@hotmail.com
[2]Jsf Empreendimentos Florestais Ltda, Costa Rica, Mato Grosso do Sul, Brasil – juniorfarias.3@hotmail.com
[3]Universidade Federal do Espírito Santo, Departamento de Ciências Florestais e da Madeira, Jerônimo Monteiro, Espírito Santo, Brasil – niltoncesarfiedler@yahoo.com.br

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Resumo

Modelagem do comportamento do fogo em vegetação herbácea no Cerrado brasileiro. O conhecimento das variáveis que influenciam o comportamento do fogo permite a criação de modelos para simular a propagação do fogo na paisagem e integrar informações sobre os principais conjuntos de fatores diretamente relacionados ao fenômeno. O objetivo da presente pesquisa foi mensurar os parâmetros do comportamento do fogo em queimas experimentais em condições de campo, a fim de estabelecer correlações entre as variáveis do fogo e fatores ambientais para a elaboração de modelos de previsão do comportamento do fogo. As queimas experimentais foram realizadas na zona rural do município de Currais-PI no final do período chuvoso em maio de 2021. Foram definidas na área 40 parcelas de 10 m x 2 m com distribuição homogênea da vegetação e dispostas na direção do vento predominante da região. A variável meteorológica velocidade do vento apresentou maior relação com os parâmetros do comportamento do fogo e o tempo de queima é a variável mais importante nos modelos preditivos. As variáveis ambientais têm boa capacidade preditiva para estimar a velocidade e intensidade do fogo. Para a altura das chamas, recomenda-se considerar variáveis da vegetação no modelo. A análise e síntese dos resultados da queima experimental possibilitou conhecer o comportamento do fogo em vegetação herbácea nos domínios do Cerrado brasileiro, sendo essencial para a realização de práticas adequadas de manejo do fogo e constituindo um elemento central de todo o manejo dos incêndios florestais.
Palavras-chave: Queimas experimentais, fatores ambientais, modelos de previsão, manejo do fogo, proteção floresta.

Abstract

Understanding the variables accounting for influencing fire behavior enables developing models to simulate fire spread over landscapes, as well as integrating information on the main sets of factors closely related to this phenomenon. The aim of the present study is to measure parameters of fire behavior in experimental burns carried out under field conditions to establish correlations between fire variables and environmental factors to develop fire behavior-prediction models. Experimental burning was carried out in the rural area of Currais municipality-PI, at the end of the rainy season, in May 2021. Forty (40) plots (10 m x 2m) presenting homogeneous vegetation distribution arranged in the prevalent wind direction of the investigated region were defined in the study site. The meteorological variable 'wind speed' presented higher correlation to fire behavior parameters, whereas burning time was the most important variable in the herein tested predictive models. Environmental variables presented good predictive capacity to estimate fire spread speed and intensity. With respect to flames' height, it is recommended taking into consideration vegetation variables in the model. The analysis and synthesis applied to results of the experimental burning enabled understanding fire behavior in herbaceous vegetation in the Brazilian Cerrado domain. This finding turns it into an essential element at the time to carry out adequate fire management practices, as well as core element of the entire forest fire- management process.
Keywords: Experimental burning; environmental factors; prediction models, fire management; forest protection.

INTRODUCTION

Fire, as combustion form, is a complex process involving the association of air oxygen with carbon in the fuel, and it is triggered by a source of ignition or heat. This phenomenon is closely linked to climate conditions, such as low relative humidity, rainfall shortage, high temperatures and wind – all these conditions create favorable conditions for both the incidence and spread of fire events.

Although fire plays key role in maintaining natural and artificial ecosystems, wildfire can lead to permanent disturbances and cause substantial material losses and damages. According to Herawati and Santoso (2011), forest fires bring along issues at different scales. At local scale, they contribute to vegetation degradation, affect biodiversity, lead to economic losses, and even result in loss of lives. At regionally scale, the smoke generated by these fire events poses health-related risks and affects transportation processes. At global

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scale, forest fires increase carbon dioxide emissions and potentially affect the planet's climate.

Fire is often used for land management purposes, mainly for agricultural and livestock purposes (ROCHA; NASCIMENTO, 2021) in Brazil, where most biomes are susceptible to burning (JESUS *et al.*, 2020), with emphasis on the herbaceous savannah vegetation in the Cerrado biome. The Brazilian Cerrado, which is known for its remarkable biodiversity, has faced threats to its ecological balance due to indiscriminate use and increased frequency of fire events in recent decades (SCHMIDT; ELOY, 2020). According to the MapBiomas survey (2021), Cerrado was the biome mostly affected by fire events between 2000 and 2019; according to estimates, 41% of its area was affected by this phenomenon.

Empirical fire behavior models help better understanding the intricate relationship between fire and the environment. These models are fundamental tools used in fire management processes, since they can help developing controlled burning plans and strategies focused on preventing and fighting forest fire. Moreover, they help better understanding how fire responds to climate change, if one takes into consideration the relative influence of both biotic and abiotic factors on fire events.

According to Batista *et al.* (2013), several countries, such as Brazil, keep on developing fire behavior estimates based on empirical models that often comprise burning experiments. These studies aim at simulating fire propagation and at integrating information about key factors like vegetation, topography and weather conditions. They help estimating fire behavior, predicting the fire risk degree and determining the likelihood of ignition under field conditions (CACHOEIRA *et al.*, 2020).

Fire-front propagation speed stands out as the most crucial information for fire brigade chiefs among the variables assessed by these models. This information helps formulating effective firefighting strategies, mainly in the case of large fire events, since they increase the risks to firefighters. Climate is the most dynamic among the three factors influencing fire behavior. Studies focused on comparing both the significance and influence of environmental variables on different fire behavior parameters, such as intensity, propagation speed and flame height, remain scarce in the literature (BATISTA *et al.*, 2013; CANSLER and MCKENZIE, 2014; FANG *et al.*, 2015; PARKS *et al.*, 2014; RODRIGUES; TORRES, 2020). On the other hand, some studies suggest that the relative contributions of environmental variables to fire behavior can significantly change across spatial scales (FANG *et al.*, 2015; LIU *et al.*, 2013).

In light of the foregoing, the aim of the current study was to determine fire behavior parameters in experimental burns carried out under field conditions. It was done to establish correlations between fire variables and environmental factors in order to help developing fire behavior-prediction models. Such models play essential role in effective wildfire management processes, since they provide valuable insights into the complex interplay between environmental conditions and fire behavior.

MATERIAL AND METHODS

Study site

Controlled experimental burns were carried out in the rural area of Currais municipality, Piauí State (coordinates 8º41101.02" S and 44º46'54.36" W). The terrain of the experimental site is flat, and its vegetation is mostly featured by spiked crinkleawn (*Trachypogon spicatus* (L.f) Kuntze) falling within the Cerrado grassland formation (Figure 1).

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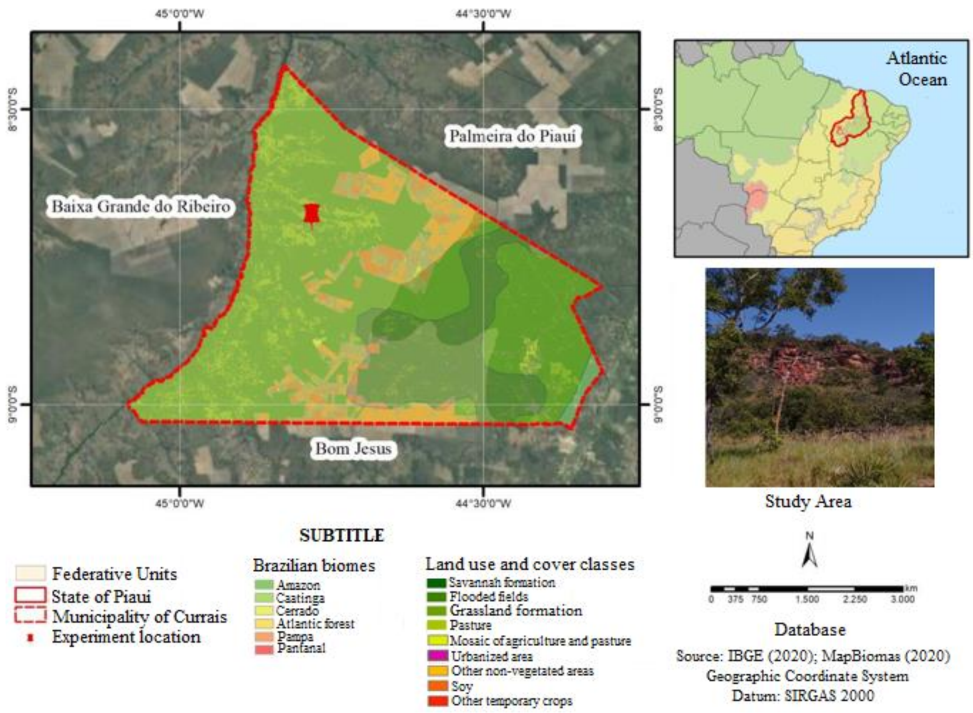

Figure 1. Spatial location of field plots used to carry out experimental burns in *Trachypogon spicatus* (L.f) Kuntze vegetation.

Figura 1. Localização espacial das parcelas de campo para realização das queimas experimentais em vegetação de *Trachypogon spicatus* (L.f) Kuntze.

Establishing the plots

In total, 40 plots were established for the current experiment, each one presented the following dimensions: 10m x 2m (20m²), and homogeneous vegetation distribution. These plots were strategically arranged at the regions' prevalent wind direction. Graded wooden stakes were securely positioned at 1m intervals in each plot and used as observation points to collect fire behavior data. Observations and measurements of the combustible material, meteorological variables and of the fire behavior itself (during the burning phase) were carried out in each plot. Two-meter-wide firebreaks were created around each plot based on using tools, such as hoes, machetes and rakes, to avoid fire spreading.

Monitoring weather conditions

Continuous monitoring of weather conditions was carried out in portable digital weather station, Display Touch-Screen ITWH-1080, equipped with datalogger for data storage purposes, throughout the plots' burning process. This station was configured to measure temperature, relative humidity, as well as wind speed and direction, every minute. It was strategically positioned within the maximum radius of 300 meters from the burning site. Recorded data were diligently documented for the entire duration of each plot burning

Featuring the fuel material

Information about combustible material type, amount and moisture was collected to feature this material. These data were gathered through an inventory of combustible materials deposited in the soil.

In order to do so, 4 samples were randomly allocated in the area with the aid of a 2,500cm² (50 cm x 50 cm) template. After the collection process was over, the fine combustible material was stored in plastic bags and closed, right away, to prevent moisture loss. Then, samples were weighed on precision analytical scale to determine green mass weight. Subsequently, they were dried in circulation oven with air renewal, at constant temperature of 75 °C, until reaching constant weight.

The ABNT NBR 8293 (1986) standard was used to determine the fuel material moisture content, based on equation 1:

$$U\% = \left(\frac{M_u - M_s}{M_s}\right) * 100$$

Wherein:

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U% = combustible material moisture content, expressed in %;
Mu = green material mass at collection time, expressed in g;
Ms = oven-dried combustible material mass, expressed in g.

In total, 4.0 g of combustible material from each sample was subjected to grinding in Wiley-type knife mill for calorific power determination purposes. The resulting material was, then, sieved in 35-mesh and left in acclimation room for 15 days. After this period was over, samples were analyzed in Parr 9000 digital calorimeter to determine energy content (kcal. kg^{-1}).

Useful Calorific Power (UCP) was used to calculate fire intensity. UCP accounts for the energy required to evaporate water associated with the fuel material moisture content. This correction is necessary due to loss of calorific power attributed to the presence of moisture in the material. Calorific power adjustment based on fuel's moisture content was performed based on the following formula (FERREIRA *et al.*, 2014).

$$UCP = LCP * \left(\frac{100-U}{100}\right) - 6 * U$$

Wherein:
UCP = useful calorific power, expressed in $kcal.kg^{-1}$;
LCP = lower calorific power, expressed in $kcal.kg^{-1}$;
U = moisture on wet basis, expressed in %.

Plot burnings

Plots were burned from May 27 to 30, 2021 (end of the rainy season) from 8:00 am to 12:00 pm and from 2:00 pm to 5:00 pm, based on the downwind burning technique. A drip of flammable liquid comprising a mix of diesel oil and gasoline, at 3:1 ratio, was use to ignite the combustible material.

Fire behavior variables

The following fire behavior variables were observed during the burning of each plot based on internationally adopted standard procedures.
Propagation speed – visually estimated by determining the time required for the line of fire to travel 1-m distances, previously demarcated in each plot, along its length (10 m);
Flames' Height – visually estimated mean flame height reaching every 1 m in advance of the line of fire, with the aid of graded wooden stakes.
Fire intensity – proposed by Byram (1959) and determined through the following equation: $I = H * w * r$; wherein I = fire intensity, expressed in kcal.m-1.s^{-1}; H = calorific power of fuel, expressed in $kcal.kg^{-1}$; w = fuel material weight, expressed in $kg.m^{-2}$ and, r = fire propagation speed, expressed in $m.s^{-1}$.

Data processing and analysis

Data collection and processing procedures enabled building a matrix comprising environmental (fuel and weather conditions) and fire behavior variables (Table 1).

Table 1. Environmental and fire behavior variables.
Tabela 1. Variáveis ambientais e do comportamento do fogo.

Variables	Description	Unit
Vv	Wind speed during plots' burning	$m.s^{-1}$
Ur	Relative air humidity (5 observations per plot, on average)	%
T	Air temperature (5 observations per plot, on average)	°C
TdQ	Burning time	seg
Hch	Flames' height during burning (10 observations per plot, on average)	cm
TPF	Fire spreading rate	$m.s^{-1}$
I	Fire intensity	$kcal.m.s^{-1}$

Combustible material, meteorological conditions and fire behavior data were processed in Microsoft Office Excel 2016 spreadsheets and further analyzed in RStudio software. Exploratory data analysis was performed to visualize outliers' distribution based on using boxplot graphics plotted in Ggplot2 package.

In addition, RStudio software was used for correlation analyses based on the Spearman method, as well as for stepwise analysis, which, in its turn, aimed at generating regression models to predict fire behavior variables, such as fire intensity, spreading rate and flame height - meteorological variables were used as

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explanatory factors. Optimal regression models were selected by taking into consideration the three models presenting the lowest Mallows Cp statistical coefficient. Mallows' Cp statistic was plotted against the number of parameters (p); smaller Cp value approaching p indicated less biased parameter estimates and superior model fit. Data normality was assessed through Shapiro-Wilk test, at 5% significance level, whereas multicollinearity was assessed based on variation inflation factor (VIF).

Hence, equations' selection was guided by different criteria, such as the highest adjusted coefficient of determination (R^2aj), the lowest rate of the estimate's standard error (Syx%), and the lowest Mallows Cp value.

RESULTS

Based on the exploratory analysis applied to the investigated variables (Figure 2), these variables overall presented good symmetry and values closely clustered around the median. However, variable 'Hch' (flame height) presented negative asymmetry. Moreover, this variable had higher incidence of outliers, which represented values beyond the upper and lower limits of the boxplot graphics.

Notable and pertinent features to fight forest fire became apparent in data measured and collected during the experimental burning of the investigated plots. The plot recording the lowest and the highest fire intensity values presented burning times (TdQ) of 740 and 205 seconds, respectively. This finding implies that the time necessary for the combustible material to be consumed got shorter as fire intensity increased. Therefore, these variables are strongly and negatively correlated to fire behavior, as shown in Figure 3 (r= -0.979). Similar findings were observed for Fire Propagation Rate (TPF), which presented perfect negative correlation to 'TdQ'.

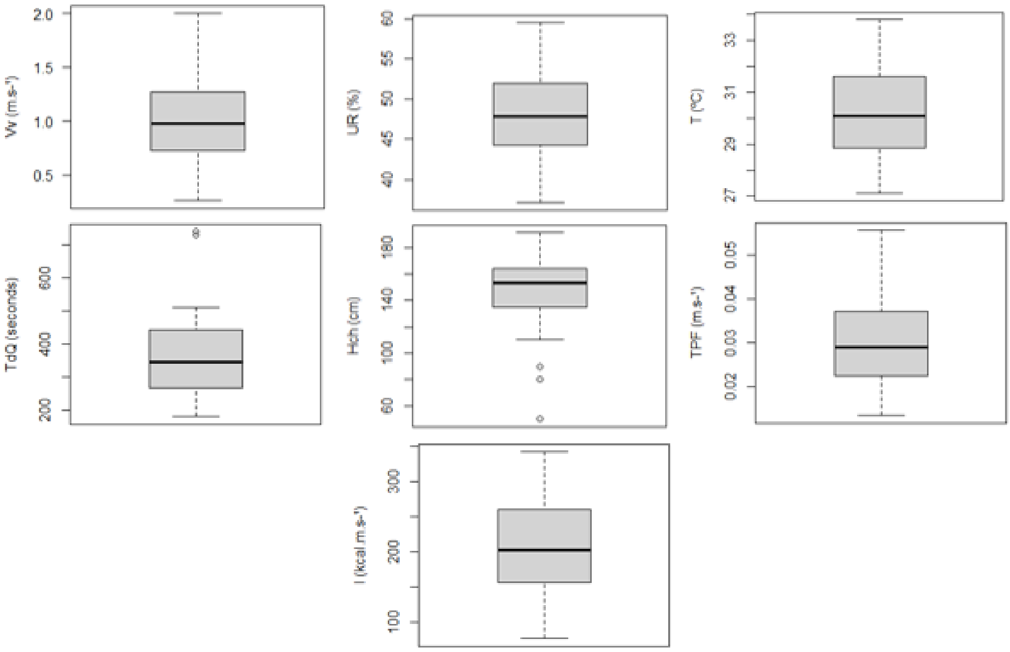

Figure 2. Boxplot graphs of variables investigated during plots' burning. Vv: wind speed, UR: relative air humidity, T: air temperature, TdQ: burning time, Hch: flame height, TPF: fire spread rate, I: fire intensity.

Figura 2. Gráfico boxplot das variáveis estudadas durante a queima das parcelas. Vv: velocidade do vento, UR: umidade relativa do ar, T: temperatura do ar, TdQ: tempo de queima, Hch: altura das chamas, TPF: taxa de propagação do fogo, I: intensidade do fogo.

Wind speed during the burning sessions reached 1.2 $m.s^{-1}$, on average; it ranged from minimum 0.26 $m.s^{-1}$ to maximum 2 $m.s^{-1}$ (Figure 2). Notably, higher wind speeds contributed to easier fire spreading and it resulted in faster propagation speed and in shorter burning time. This correlation, among all variables, is visually evident in Figure 3, which shows significant association between wind speed and the aforementioned fire behavior parameters.

Flame height (Hch) recorded values ranging from 50 to 191 cm during plots' burning (Figure 2) due to fire intensity. Results in the current study pointed out that flame height increased as fire intensity increased, and it had straight impact on firefighting efforts. Figure 3 shows significantly positive correlation (r= 0.691) between the analyzed variables, as well as between Hch x TPF (r=0.613) and Hch x TdQ (r=-0.613). This finding

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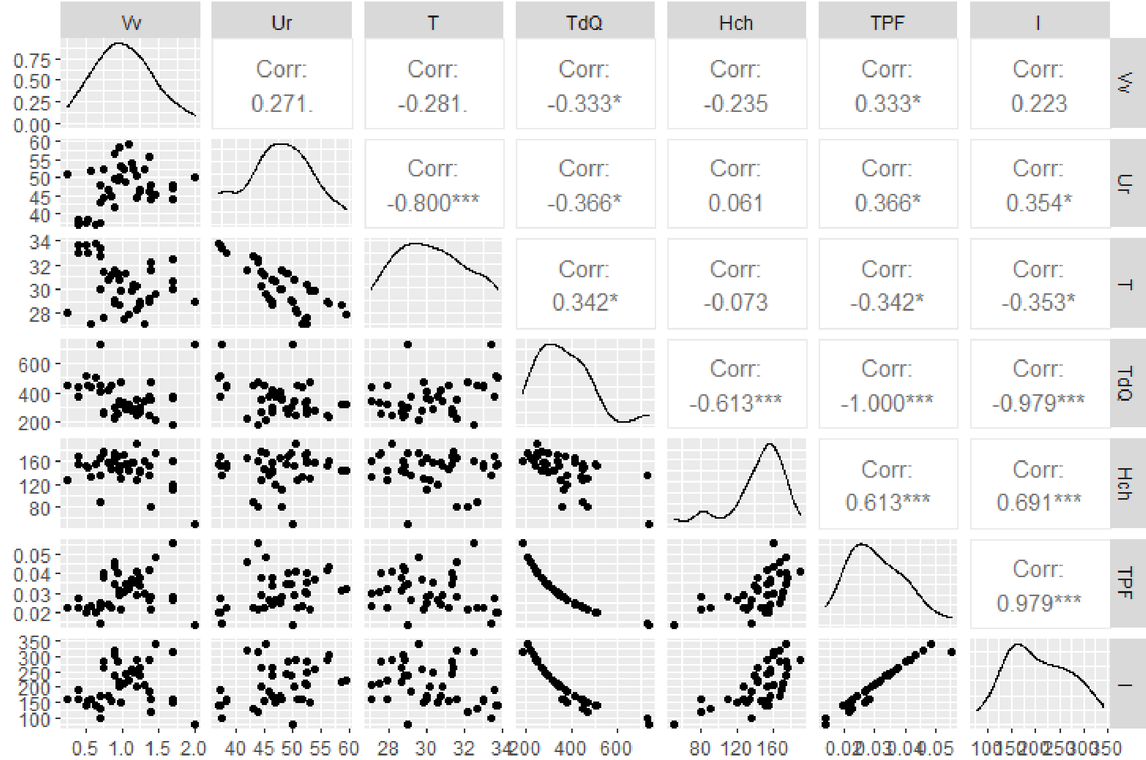
suggests that higher flame height corresponds to shorter burning time for the fire to engulf the entire area, as well as to increased propagation rate.

Strong negative correlation (r= -0.8) was observed among the environmental variables air temperature and relative humidity. These variables presented significant correlation to TdQ, at magnitudes of r= 0.342 and r= -0.366, respectively (Figure 3). Furthermore, wind speed emerged as the variable most closely related to fire behavior parameters.



*** Significant correlation in t test, at 99% confidence level; * Significant correlation in t test, at 90% confidence level.
*** Correlação significativa pelo teste t no nível de confiança de 99% de confiança, *Correlação significativa pelo test t no nível de confiança 90%.

Figure 3. Spearman correlation between environmental variables and fire behavior variables associated with plots' burning.

Figura 3. Correlação de Spearman entre as variáveis ambientais e as variáveis do comportamento do fogo relacionadas à queima das parcelas.

With respect to regression models' adjustments to fire behavior variables, Model 3 has shown the best fit based on the adopted selection criteria, as shown in Table 2. The adjustment of variable 'fire intensity' in this model comprised wind speed, burning time and flame height. Fire propagation rate was estimated based on air temperature and burning time, whereas the adjusted model for variable 'flame height' took into consideration wind speed, relative humidity and burning time. Thus, burning time was used in all the best models, and it highlighted its essential role in estimating fire behavior parameters.

Table 3 presents the results of Variation Inflation Factor (VIF) and Shapiro-Wilk tests applied to the best-fitted models developed for fire intensity, fire propagation rate and flame height. Based on the test results, the selected regression models adhered to data normality and multicollinearity assumptions. VIF values observed for each variable in the adopted equations were lower than 3, and it corresponded to lack of multicollinearity. Moreover, results of the Shapiro-Wilk Test have evidenced significance values higher than 5% ($p > 0.05$), and it confirmed normal data distribution for the best models. Most importantly, all three best-fitted models developed for fire behavior parameters have satisfied data normality and multicollinearity assumptions inherent to regression models.

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Table 2. Models used to estimate fire behavior parameters, based on wind speed "Vv" ($m.s^{-1}$), relative air humidity "Ur" (%), air temperature "T" (ºC), burning time "TdQ" (sec) and flame height "Hch" (cm).
Tabela 2. Modelos para estimar os parâmetros do comportamento do fogo, com base na velocidade do vento "Vv (m/s), umidade relativa do ar 'Ur" (%), temperatura do ar "T" (ºC), tempo de queima "TdQ" (s) e altura da chama "Hch" (cm).

Models	Fitted models	R²aj.	Syx (%)	Cp Mallows
Fire intensity				
1	I = 420.77525 – 17.38309*(Vv) – 0.35279*(Ur) – 0.65040*(TdQ) + 0.33937*(Hch)	0.9391	14.75	4
2	I = 327.09719 – 0.58272*(TdQ) + 0.57888*(Hch)	0.9364	15.07	3.2897
3	I = 393.02213 – 16.99509*(Vv) – 0.63736*(TdQ) + 0.37875*(Hch)	0.9400	14.64	2.5253
Fire propagation rate				
Models	Fitted models	R²aj.	Syx (%)	Cp Mallows
1	TPF = 5.821e-02 – 8.698e-05*(Ur) + 3.823e-04*(T) – 9.982e-05 *(TdQ)	0.9345	0.00229	2.3090
2	TPF = 7.454e-02 – 1.869e-04*(Ur) – 9.986e-05*(TdQ)	0.9340	0.0023	1.4677
3	TPF = 4.763e-02 + 5.852e-04*(T) – 9.895e-05*(TdQ)	0.9354	0.00227	0.8793
Flame height				
Models	Fitted models	R²aj.	Syx (%)	Cp Mallows
1	Hch = 194.36055 – 28.84341*(Vv) + 1.36773*(T) – 0.15925*(TdQ)	0.4543	13.06	3.9837
2	Hch = 234.5894 – 29.9761*(Vv) – 0.1530*(TdQ)	0.4502	13.11	3.1704
3	Hch = 266.42703 – 28.61354*(Vv) – 0.60663*(Ur) – 0.16509*(TdQ)	0.4709	12.86	3.0066

Table 3. Data normality analysis based on Shapiro-Wilk's W test, at 5% significance level, and variation inflation factor (VIF) for fire behavior parameters based on the selected model.
Tabela 3. Análise da normalidade dos dados pelo teste W de Shapiro-Wilk, ao nível de significância de 5% e fator de inflação de variação (VIF), para os parâmetros do comportamento do fogo de acordo com o modelo selecionado.

Model	VIF			Shapiro-wilk	
Fire intensity					
Model	Vv	TdQ	Hch	w	*p-value*
	2.16	2.58	1.93	0.97038	0.4539
Fire propagation rate					
Model	T	TdQ		w	*p-value*
	1.09	1.09		0.9499	0.1128
Flame height					
Model	Vv	Ur	TdQ	w	*p-value*
	1.42	1.19	1.5	0.9867	0.9406

DISCUSSION

The investigated environmental variables have shown clear association with fire behavior parameters, as evidenced by their inclusion in the best-fitted regression models. Higher fire intensity was estimated under lower wind speed conditions. This finding is explained by the increased rate of energy or heat released per unit of time and length along the fire front. Fire intensity is a paramount parameter often used to compare burns to forest fire.

With respect to propagation speed, high temperatures increase fire likelihood to spread fast, whereas higher flame heights are associated with lower wind speed and relative air humidity rates. Although these observations can change depending on study location and nature, Batista *et al.* (2013), Cachoeira et al. (2020), and Schmidt *et al.* (2016) observed similar associations in their adjusted models.

Weather variability plays key role in fire dynamics. Therefore, carefully planned experimental burns enable observing intricate interactions of different climatic variables, vegetation types and topography, with fire.

This empirical method is essential to acquire accurate data on fire propagation rates, flame intensity, burning patterns, among other critical aspects. Professionals can have deeper and more specific insights into fire behavior through the broad understanding of how these factors manifest under controlled experimental conditions.

The practical application of this knowledge in firefighting strategies is evident. Accurate predictions of how fire will behave under real-world conditions enable faster and more efficient response to it. Firefighting teams can anticipate fire spread, intensity and flame height rates by developing predictive models based on experimental burns. This knowledge makes the efficient allocation of resources easier and allows efforts to focus on places at the highest risk of fire events, as well as maximizing the effectiveness of firefighting operations.

Wind speed emerges as the most crucial variable among the investigated climate variables, since it enhances the combustion zone by providing more oxygen and by enabling vegetation moisture loss. Moreover, wind interacts with the convection column, as well as disperses sparks and embers that can potentially cause additional fire events (ICMBio, 2010). It also determines fire propagation form and direction.

Results in the current study have evidenced slow-to-medium speed burn, as reported by Botelho and Ventura (1990). The strategy recommended to fight potential fire events lies on implementing operational work based on the parallel method (ICMBio, 2010) and it emphasizes the relevance of advanced knowledge of fire based on weather conditions in the investigated area. This method comprises building a firebreak line at a varying distance from the flames, typically longer than three meters, parallel to the fire's advance, mainly on the flanks. The goal of this procedure is to shorten the length of the wedge-shaped head. The construction of this line can be followed by fire application (counterfire) to rule out materials interspersed with the fire front and, therefore, to increase the strip devoid of fuel.

Although fire propagation speed significantly changes from one fire event to another due to several factors, results have been reported by several authors, under different burning conditions. According to Soares (2017), it can range from 0.005 $m.s^{-1}$ to 0.01 $m.s^{-1}$ in controlled burns, as well as reach 5 $m.s^{-1}$ in large fire events. Results in the present study have evidenced that fire burning herbaceous vegetation in the Cerrado biome recorded higher propagation speed than that observed for other fuel types and environmental conditions. This hypothesis is supported by findings in other studies, such as those by Alves *et al.* (2018), Batista *et al.* (2013), and Sow *et al.* (2013).

Fire intensity is one of the most comprehensive fire descriptors, since it leads to potential damage under specific conditions. Several researchers described fire behavior based on a scale of different intensity levels. According to Alexander (2000) classification, which establishes generalized limits on fire suppression effectiveness in comparison to fire intensity, burning results have suggested that controlling the fire in the investigated area would require using pressure water and/or heavy machinery.

It is essential understanding flame height at the time to determine the safe distance from the fire during firefighting operations. According to Butler and Cohen (1998), the safety zone for firefighters in front of the fire line should be at least 4 times the flame height, based on the radiant energy of the fire. Results in this study have evidenced that firefighter's safety distance in the plot-burning scenario ranged from 2 to 7.64 m. In other words, low-intensity burn, in association with slow spreading speed and low flame height, enables firefighters to safely approach the fire line and use backpack pumps, beaters, among other equipment and hand tools to effectively control the fire events.

When it comes to regression model adjustments, environmental variables presented robust predictive capacity to estimate fire propagation speed and intensity, as evidenced by the observed determination coefficient. Although variations in results are often expected in studies based on different collected variables, burning conditions and vegetation types, it is noteworthy that the regression models developed for these fire behavior parameters in the current study presented better model fit than those reported in studies available in the literature.

According to Batista *et al.* (2013), the adjusted model for fire intensity recorded R^2 equals to 0.85 based on flame height and relative humidity. The experimental study carried out with Cerrado vegetation by Schmidt et al. (2016), between May and July 2014, developed fire intensity prediction models with R^2 values equal to 0.53 and 0.33. Another study conducted by Sow *et al.* (2013) involved 231 prescribed burns in three savannah ecosystems in Senegal and it resulted in a model presenting R^2 equal to 0.54, according to which, fuel load, wind speed and grass cover were identified as the variables mostly influencing fire intensity.

Estimating fire propagation rates is a challenging task due to different environmental factors associated with fire spreading. Batista *et al.* (2013) conducted an experiment in a *Pinus elliottii* stand, and developed models with R^2 values ranging from 0.82 to 0.87. Rodrigues and Torres (2020) assessed fire behavior in 80 burning plots within a 10-year-old hybrid *Eucalyptus urophylla* and *Eucalyptus grandis* plantation and recorded high R-squared values based on using machine learning algorithms. Variables, such as fine fuel humidity, days without rain, and air temperature, proved to be the most significant in the adjusted models. Hence, the number of variables and their ease of collection should be used as criteria in model development processes. Moreover, traditional statistical methods are capable of providing well-adjusted equations applicable to new datasets.

With respect to flame height, it is recommended using a larger number of sampling units to better understand weather influence on this fire behavior parameter. Visually reading flame height is a challenging task because incident radiation makes it hard to approach the burn line. However, model accuracy can be improved by incorporating additional explanatory variables to it. Studies have emphasized the significant role played by living and dead fuel material biomass in estimating flame height (Batista et al., 2013; Cachoeira et al., 2020). Notably, burning time consistently appeared in all top models, a fact that emphasized its essential role in developing predictive models for fire behavior in herbaceous vegetation grown in the Brazilian Cerrado.

The comparison between the current results and those observed in other studies highlights the need of taking into consideration potential differences in estimates of fire behavior parameters and independent variables in the developed models at the time to plan optimized fire control strategies. This consideration is of paramount importance given specific conditions comprising both environment and fire features in each location.

Future studies should take into consideration vegetation features in each plot, as well as incorporate this information as input to predictive models. Differences in vegetation density, height and type have significant influence on the amount of fuel available to burn. Furthermore, vegetation moisture plays critical role in its combustibility; drier and dead vegetation are more flammable and contribute to fast fire spreading. The interaction between fire and weather is so intense that recent studies, such as that carried out by Torres *et al.* (2019), have emphasized the incorporation of associations between meteorological elements and combustible material moisture as independent biophysical variables in the developed models. These variables have direct link to fire behavior, besides providing more insightful predictions than any meteorological variable, alone. Models fueled by data resulting from experimental burns are powerful tools to be used for integrated fire management purposes, since they contribute to communities and ecosystems' safety.

CONCLUSIONS

- Based on the current findings, meteorological variable 'wind speed' presented strong association with fire behavior parameters, whereas burning time was the most important variable in the herein developed predictive models.
- Environmental variables have good predictive capacity to estimate fire propagation speed and intensity. It is recommended taking into consideration additional explanatory variables when it comes to flame height.
- The analysis and synthesis applied to results of experimental burns enabled understanding fire behavior in herbaceous vegetation in the Brazilian Cerrado. This finding turns fire behavior into essential element at the time to carry out adequate fire management practices, as well as core element of the entire forest fire-management.
- Thus, once forest managers understand the field variables, they can use the herein determined mathematical models in areas presenting vegetation features similar to those in the current study to estimate fire behavior parameters.

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