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Relationships and Modeling of Cerrado Grassland Fuel in Jalapão, Tocantins state, Brazil

Relaciones y modelación del combustible de pastizales del Cerrado en Jalapão, estado de Tocantins, Brasil

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Highlights

- This study reveals the vital role of dead grass fuel load in fire consumption models.
- Non-destructive variables are crucial for estimating the live and dead fuel load in the Cerrado biome.
- The results show the influence of dead grass load on the development of fire risk models for protected areas.
- Equations with R^2aj values ranging from 0.12 to 0.73 demonstrate a variable impact on live and dead fuel estimation.
- This study on the Jalapão emphasizes dead grass as a key factor in forest fire dynamics.

Abstract

The aim of this study was to understand the relationships between different destructive (grass and 1-h fuel load) and non-destructive fuel variables (grass height, litter height, number of species, and number of individuals), in order to develop models for estimating fuel load and moisture and analyzing fuel consumption. This study was carried out in a protected area located in the Cerrado biome, in the Jalapão region,

Tocantins state, Brazil. The non-destructive characteristics of the vegetation were sampled to determine the live and dead fuel loads in different time-lag classes. Equations were obtained to estimate these loads, with values of R^2aj, varying from 0.12 to 0.73. The considerable influence of dead grass fuel load on modeling could be observed, which is regarded as the main determining factor for a greater consumption of vegetation by fire.
Keywords: forest fires, fuel consumption, fuel load estimation.

Resumen
El objetivo de este estudio fue comprender las relaciones entre las diferentes variables de combustible destructivas (pasto y carga de combustible de 1-h) y no destructivas (altura del pasto, altura de la hojarasca, número de especies y número de individuos), en aras de desarrollar modelos para estimar la carga de combustible y la humedad y analizar el consumo de combustible. Este estudio se llevó a cabo en un área protegida ubicada en el bioma Cerrado, en la región de Jalapão, estado de Tocantins, Brasil. Se muestrearon las características no destructivas de la vegetación para determinar las cargas de combustible vivo y muerto en diferentes clases de retardo. Se obtuvieron ecuaciones para estimar estas cargas, con valores de R^2aj que varían entre 0.12 y 0.73. Se pudo observar la influencia considerable de la carga de combustible de pasto muerto en el modelado, la cual se considera el principal factor determinante para un mayor consumo de vegetación por el fuego.
Palabras clave: incendios forestales, consumo de combustible, estimación de la carga de combustible.

INTRODUCTION

Fuel is the organic matter available for ignition and combustion, as well as the only factor related to fire that is subject to control by human action (Soares *et al.*, 2017). The description and quantification of fuel are important factors to correctly understand the behavior of fire and produce relevant information for its management in terms of conducting prescribed burns, fire suppression activities, and danger assessments of forest fire occurrence. The knowledge of fuel characteristics also allows for the construction of models for carbon determination (Gould *et al.*, 2011). According to Keane *et al.* (2012), effective fire management depends on a comprehensive, consistent, and accurate description of the fuel, which consequently dictates the behavior and effects of fire on vegetation.

Fuel can be described in terms of its physical characteristics, such as load, depth, height, and density, as well as according to its mineral content (Keane *et al.*, 2012). According to Parresol *et al.* (2012), fuel load is a critical component that has a considerable influence on the extent of fires, and Keane *et al.* (2013) highlighted that fuel load information is necessary for the majority of applications involving forest fires, as well as for understanding the effectiveness of fuel load reduction measures (Cawson *et al.*, 2017). However, regions such as the Cerrado biome have limited studies that consider the characteristics of the surface fuel in order to generate data for proper management.

The Cerrado is the second most extensive ecosystem in South America and Brazil, recognized as the richest savannah in the world in terms of biodiversity and covering an area of 204.7 million ha (about 22% of the territory of Brazil) (Durigan & Ratter, 2016). It is regarded as the richest savannah in the world, harboring about

13 144 species of flora, representing 36.9% of the plant species currently known to science and listed in the flora of Brazil, as well as 4.8% of the world flora (Strassburg *et al.*, 2017). The Cerrado is an environment prone to fire; it is the one that burns the most in all of Brazil. It is subject to a regular and predictable dry period from May to September, which constitutes the major cause of large fires in this environment, mainly due to high temperatures and a low relative humidity (Franco *et al.*, 2014). All the biodiversity, the heterogeneity of the vegetation, and its great extension make the management of fire in the Cerrado a highly complex task.

Obtaining quantitative information such as load is spatially and temporally complex (Keane *et al.*, 2013). Surveying such variables in large areas is technically and financially unfeasible (Duff *et al.*, 2012). Thus, indirect methods, such as biophysical modeling, can be used to estimate difficult-to-obtain parameters (***e.g.***, Parresol *et al.*, 2012; Santana & Marrs, 2014; Lydersen *et al.*, 2015). Duff *et al.* (2012) stated that, because fuel is a consequence of the vegetation properties in a given location, it is indisputable that biophysical models can be used to predict the quantitative attributes of the fuel.

Studies involving fuel modeling are uncommon and are generally performed with different objectives, such as predicting the rate of the increment (Gould *et al.*, 2011), estimating the surface fuel load based on bed height (Battaglia *et al.*, 2010), and assessing the relationships between vegetation composition and fuel quantity (Duff *et al.*, 2012; Parresol *et al.*, 2012). In Brazil, studies involving fuel modeling are limited to the southern region of the country and relate to estimates of the surface fuel loads in Araucaria, Pinus, and Eucalyptus forests (Beutling *et al.*, 2012). Studies on surface fuel in the Cerrado are rare.

Among its various characteristics, knowledge of fuel moisture is essential for quantifying the risk of fire occurrence and serves as an important variable in fire behavior models (Cawson *et al.*, 2017; Prichard *et al.*, 2017). In the context of the Cerrado, especially in campestral environments, fuel moisture modeling is of great importance, considering that the moisture condition of the grassy vegetation in this environment is one of the main factors for the occurrence of fires in the biome (Pereira Junior *et al.*, 2014). The moisture content of fuel affects fire behavior by controlling flammability, propagation speed, available fuel level, and fire intensity (Slijepcevic *et al.*, 2015). In the long term, humidity influences the frequency of fire occurrence, and, if the fuel load is sufficient, fires will occur more consistently in areas with drier vegetation (Cawson *et al.*, 2017).

The methods used to obtain fuel moisture content are often complex, so there is an ongoing search for strategies aimed at developing operational models to understand this variable. According to Matthews (2014), there are two main approaches for modeling the moisture content of fuels: empirical models and process-based models. The former are defined as those that use statistics to build relationships between the moisture content and the input variables (weather conditions, load, and site characteristics) obtained from field surveys.

The development of empirical models that relate the moisture content of fuel to meteorological variables has advanced with studies on Amazonian tropical forest litter, dead fuels from grasslands in Australia (buttongrass moorlands) (Marsden-Smedley & Catchpole, 2001), and pine areas in particular (Lin, 2004; Alves *et al.*, 2009). There is a clear need for research aimed at understanding the relationship between fuel moisture and meteorological variables in Cerrado grassland physiognomies, given the lack of works in this regard.

The knowledge of these dynamics is important for establishing a possible fuel moisture model based on local meteorological variables.

Another important factor closely linked to the characteristics of fuel is related to its consumption by fire. As highlighted by Prichard *et al.* (2014), consumption is a critical component in estimating emissions from forest fires, in measuring the effectiveness of a prescribed burn in reducing fuel load, and in determining the amount of heat released, fire severity, and other effects. Ottmar (2014) stated that fuel consumption during a fire is a basic process that leads to greenhouse gas emissions in greater or lesser proportions and consequent impacts on the atmosphere. Except for the study by Castro and Kauffman (1998), who highlighted the influence of the herbaceous component of grassland and savanna vegetation on fire behavior variables and consumption rates in the Cerrado, little is known about the actual participation of these characteristics (Simpson *et al.*, 2015) or about the influence of the dry season and the non-burning period.

This study aimed to understand the relationships between fuel load variables in different classes (grasses and 1-h fuel), *i.e.*, live and dead, and non-destructive variables such as grass height, litter height, number of species, and number of individuals, as well as to develop models to estimate fuel load and moisture and analyze the intrinsic fuel characteristics with the greatest influence on consumption by fire, such as grass height, litter height, dead grass fuel load, 1-h dead fuel load, and total dead fuel load. All this, for a campestral area of the Cerrado in the Jalapão region. This work was based on the following hypotheses: (i) grass height is related to grass fuel load variables (dead and live); (ii) litter height is related to the wood debris load variables of the time-lag class; (iii) fuel moisture responds significantly to variations in temperature and relative air humidity; (iv) regarding the intrinsic characteristics of the fuel, under conditions of lower humidity, the material in the grass layer has the greatest influence on the rate of fuel consumption by fire.

MATERIALS AND METHODS

Study area

This study was conducted in the south-central portion of the Serra Geral do Tocantins Ecological Station (EESGT). The EESGT is an integral protection conservation unit located in the Cerrado biome in the Jalapão region, covering 716 306 ha. It is in the northern region of Brazil, under the central coordinates 10°54'09.70"S, 46°41'49.65"W (datum WGS 84). This station covers the municipalities of Almas, Mateiros, Ponte Alta, and Rio da Conceição in the state of Tocantins and the municipality of Formosa do Rio Preto, which belongs to the state of Bahia. According to the Köppen classification, the climate of the region is of the Aw type (tropical savanna climate), with annual precipitations ranging from 1400 to 1500 mm (Seplan, 2012), which is higher than the potential annual evapotranspiration. The summer is rainy and occurs between October and April, and dry winters occur from May to September (ICMBio, 2014).

The predominant phytophysiognomy of the Cerrado is grassland, including dry ('campo limpo seco', 'campo sujo seco', and 'campo rupestre') and wet ('campo limpo úmido' and 'campo sujo úmido') grasslands

(Pereira Junior *et al.*, 2014). The predominant soil type is quartz sand or quartzarenic neosol, which has a sandy texture down to least 2 m deep, with up to 15% clay. The relief varies from relatively flat to gently undulating, with average elevations between 300 and 550 m (Santos *et al.*, 2013).

Treatments and procedures for collecting variables

The treatments were based on fuel collections spanning four months of the dry season (May, June, August, and September) in areas with four periods without fires (fuel age), ranging from one to four years. Predominantly, the rural areas located in the EESGT are regions with no-burning periods of one up to four years, as a result of integrated fire management actions (MIF).

No-burning periods were determined using remote sensing techniques and Landsat 8 OLI satellite images, analyzing the burn scars reported in the EESGT. Thus, throughout the experiment, 128 plots, called *data sampling units*, were installed.

Each data sampling unit was defined by two 30 m transects, distributed by drawing lots, containing eight sub-samplings called *fuel sampling plots*, each with an area of 0.25 m² (0.5 m x 0.5 m) (Silva *et al.*, 2018). The size defined for the fuel sampling plots aimed to ensure a broad sampling and greater variability in the sampled fuel. The transects were separated by 14 m, and the location of the fuel sampling plots in each transect was marked every 6 m. In these markings, it was possible to install up to two plots, one at 1 m to the right of the transect line and the other at 1 m to the left of the transect line (Santos *et al.*, 2020). The samples were taken in both the fuel (before the fire) and fuel consumption (after the fire) stages.

At the end of the study, 1024 fuel sampling plots had been analyzed (128 sampling units with eight fuel sampling plots each). To obtain the fuel load values, the units were converted from kg m² to $Mg.ha^{-1}$ for each data sampling unit. Meanwhile, for the quantification of species and total individuals, no conversions were performed, and the original size of the sample was considered (0.25 m²).

Before sampling via the destructive method, measurements of grass height (Htg, cm) and litter height (Htl, cm) were taken, with two measurements for each of these variables in order to determine their average value. The number of species (Nsp) and the number of individuals (Nin) in each 0.25 m² sample were also collected using the aerial part of each plant while avoiding the duplication of individuals, considering that two or more stems could belong to the same individual. If it was unclear how many plants were involved, part of the surface layer of the soil was removed for further study. Species were differentiated based on visual inspection, as detailed identification was not required to meet the objectives and hypotheses. Htg, Htl, Nsp, and Nin were considered to be non-destructive variables in this study.

At the time of collection, information on temperature (°C) and relative humidity (%) was obtained from a portable meteorological station (Kestrel 4200 Pocket Air Flow Tracker), which was installed near the fuel collection site, and recorded in a field form.

Surface fuel sampling

The fuel sampling plots were destructively separated according to their physiological state (live and dead) and their diameter class (time-lag), following the methodologies proposed by Schroeder and Buck (1970). Thus, live fuels were classified according to the following classes: (i) live grass fuel (Lg): annual or perennial grasses and herbs in an active physiological stage; (ii) 1-h live fuel: all live woody material with a diameter of less than 0.7 cm and leaves; (iii) 10-h live fuel: live woody material with a diameter ranging from 0.7 to 2.5 cm; and (iv) 100-h live fuel: live woody material with a diameter ranging from 2.5 to 7.5 cm.

Similarly, dead fuels were classified as follows: (i) dead grass fuel (Dg): physiologically inactive grasses and herbs or perennials; (ii) 1-h dead fuel: all dead woody material with a diameter of less than 0.7 cm and senescent leaves; (iii) 10-h dead fuel: dead woody material with a diameter ranging from 0.7 to 2.5 cm; and (iv) 100-h dead fuel: dead woody material with a diameter ranging from 2.5 to 7.5 cm. However, for the classes 10-h live, 100-h live, 10-h dead, and 100-h dead fuel, the load values were not discussed, as they reported nonsignificant amounts in relation to the others, making it impossible to carry out statistical analyses. Dead leaves deposited on the soil were included in the 1-h dead fuel class. In addition to analyzing these variables, the values for the total live fuel load (Tl), the total dead fuel load (Td), and the total fuel load (Tl+Td) were examined across areas with varying fuel ages and during different months of collection.

A subsample for each fuel class was placed in a numbered kraft paper bag, and its mass was determined using a digital scale. The subsamples were then dried in a laboratory oven until they reached a constant weight for the subsequent determination of their dry mass and fuel moisture content. The fuel moisture was determined from the ratio of the difference between the wet and dry mass on a dry basis, which was transformed into a percentage.

Fuel consumption information

Eight fuel consumption parcels were drawn and demarcated, similarly to the demarcation of the fuel parcels. After sampling the fuel, controlled burns were conducted in each data sampling unit, and basic information was collected to determine the fire behavior. This study focused on analyzing the intrinsic characteristics of the fuel and the time of collection that best contributed to its consumption by fire.

After the controlled burns, the waste materials were collected. Fuel consumption was quantified for plots with an area of 0.25 m^2, from which all the residual material was collected. The finer residues deposited on the ground were removed with the aid of a brush, a shovel, and a sieve to filter any soil particles that might cause variations in the sample mass.

The consumption samples were placed in plastic bags, identified, and sent to the laboratory for further drying in an oven until they reached a constant mass. The dry sample masses were then measured using a precision scale, and the amount of dry waste material in the fuel was determined.

Statistical analysis of the data

The statistical analyses of the data obtained in this work were carried out using the R Statistical Software (v4.1.0; R Core Team, 2021). To understand the relationship between the moisture of the fuel and its changes according to variations in the temperature and relative air humidity, as well as the relationship between destructive and non-destructive characteristics, Pearson's linear correlation analysis was performed. This analysis was performed with all fuel variables obtained, aiming to identify those with significant correlations ($p<0.05$; $p<0.01$) (Parresol *et al.* 2012).

Knowing the parameters with the highest correlation, adjustments were made to the regression equations for estimating the load and moisture variables of the fuel classes, which were classified as dependent variables. Since they showed no significant quantities, no statistical analyses of correlation and regression were performed for 10-h live, 100-h live, 10-h dead, and 100-h dead fuels.

A stepwise method was used to adjust the linear regression equations. The best equations were chosen by analyzing the highest values for the adjusted coefficients of determination (R^2aj) and the lowest values for both the absolute standard error of the estimate (Syx) and its percentage form (Syx%). To analyze the residuals, standardized residuals with a mean of zero and a variance approximately equal to one were used. Values outside the range of -3 to 3 were considered as outliers.

To assess the percentage (%) of fuel consumed by fire (Cos) and the dry waste material (Dw in $Mg.ha^{-1}$), a principal components analysis (PCA) was employed, which was based on the correlation matrix (Battaglia *et al.*, 2010; Santos *et al.*, 2018). Adjustments were also made to the linear regression models to estimate Cos and Dw based on the studied destructive and non-destructive variables. The PCA aimed to determine the fuel variables (before the fire) that most influenced the amount of fuel consumed, such as grass height (Htg), litter height (Htl), dead grass fuel load (Dg), 1-h dead fuel (Df1), and total dead fuel (Td). Thus, we considered separating the fuel by age characteristics (1 to 4 years), by month of collection (May, June, August, and September), and by fuel class.

RESULTS

This section presents the correlation and linear regression analyses for estimates of surface fuel load and fuel moisture from meteorological variables. In addition, the results of the PCA are presented, with the aim of identifying the fuel variables that exert the most significant influence on consumption by fire. In general, the linear correlations between the live and dead fuel load classes and the non-destructive variables (grass height, litter height, number of species, and number of individuals) were in the range of r = -0.44-0.76, and the R^2aj values of the linear regression equations ranged from 0.04 to 0.73. Meanwhile, the correlations between the meteorological variables and fuel moisture were in the range of r = -0.34-0.41, and the regression equations reported R^2aj values between 0.09 and 0.14. The results of the PCA showed a strong influence of grassland-stratum fuels on the rate of consumption after the fire.

Linear correlations

The total fuel load, with a coefficient of variation (CV%) = 12.34, ranged from 1.93 to 11.77 $Mg.ha^{-1}$. The surface fuel load values ranged from 0.19 to 1.97 $Mg.ha^{-1}$ for live grass fuel (Lg; CV%=7.00) and from 0.3 to 3.9 $Mg.ha^{-1}$ for 1-h live fuel (CV%=26.15). The estimates of dead grass fuel (Dg; CV%=7.62) ranged from 0.0 to 2.8 $Mg.ha^{-1}$ and, for 1-h dead fuel (CV%=27.07), a variation of 0.17-4.1 $Mg.ha^{-1}$ was observed.

Table 1 shows the Pearson linear correlation coefficients between the fuel load (total and by diameter class) and the variables of the non-destructive method, *i.e.*, grass height (Htg), litter height (Htl), number of species (Nsp), and number of individuals (Nin).

Table 1. Linear correlations between fuel load and non-destructive characteristics, as obtained during evaluations conducted in the region of Jalapão, Tocantins, Brazil

Category	Class	Non-destructive characteristics			
		Grass height	Litter height	Number of species	Number of individuals
Live	Grass	-0.0608	-0.2151*	0.0277	0.0006
	1-h fuel	0.2833**	0.3122**	0.2568**	0.1716
	Subtotal	0.2930**	0.1802*	0.1353	0.0989
Dead	Grass	0.6840**	0.4398**	-0.4431**	-0.3394**
	1-h fuel	0.4492**	0.7557**	-0.0746	-0.1984
	Subtotal	0.6164**	0.7129**	-0.2474**	-0.2674**
Live and dead	Total	0.6116**	0.6343**	-0.1290	-0.1612

***** $p < 0.05$; ** $p < 0.01$

The highest correlations for the non-destructive characteristics were observed between the dead and the total fuel variables. Thus, for dead grass fuel, significant correlations ($p<0.01$) with all non-destructive characteristics were observed. For live fuels, less significant correlations with non-destructive characteristics were noted when compared to dead fuels. The number of species and the number of individual variables showed significant inverse correlations with certain dead fuel variables, particularly the grass fuel load and the dead fuel subtotal.

Linear regression analysis

Table 2 presents the adjustments of the linear regression equations for the indirect estimation of the fuel load variables in their classes. In general, the dead fuel variables (dead grass fuel, 1-h dead fuel, and total dead fuel) showed better results with respect to the adjusted coefficient of determination (R^2aj) and the standard prediction error in absolute and percentage form (Syx and Syx%). This, in comparison with the live fuel variables.

Table 2. Adjusted regression equations for estimating the fuel load during evaluations conducted in the Jalapão region, Tocantins, Brazil

Dependent variable	Regression equations	R^2aj	Syx	Syx%
Live grass fuel	1.0848+(-0.2029)*Htl+ε	0.04	0.38	39.16
1-h live fuel	-0.8670+(0.3779)*Htl+(0.2001)*Nsp+(0.0281)*Htg+ε	0.23	0.58	39.39
Total live	0.0886+(0.0435)*Htg+(0.1835)*Nsp+ε	0.12	0.85	33.39
Dead grass fuel	0.5767+(0.0555)*Htg+(-0.0172)*Nin+(0.5221)*Htl+(-0.1671)*Nsp+ε	0.63	0.45	39.05
1-h dead fuel	-0.4206+(1.5391)*Htl+(0.0353)*Htg+ε	0.64	0.55	36.02
Total dead	0.0626+(2.2581)*Htl+(0.0902)*Htg+(-0.1986)*Nsp+ε	0.73	0.79	28.92
Total	-0.0059+(2.4735)*Htl+(0.1313)*Htg+ε	**0.62**	**1.21**	23.01

Note: Htg = grass height; Htl = litter height; Nin = number of individuals; Nsp = number of species; R^2aj = adjusted coefficient of determination; Syx = standard prediction error; Syx% = percent standard prediction error; and ε = model error

The equation for estimating the total dead fuel (Td, $p<0.001$) reached the highest value of R^2aj, with a Syx% of 28.92. Dead grass fuel and 1-h dead fuel showed similar R^2aj values, with Syx% = 39.09 and 36.02, respectively. In the equation adjusted for estimating the total fuel, the value of R^2aj was close to those observed for dead grass fuel and 1-h dead fuel, but with the lowest value of Syx% (23.01). Figure 1 shows the graphs with the distribution of the standardized residuals of the equations adjusted to estimate the load of the different fuel variables under study.

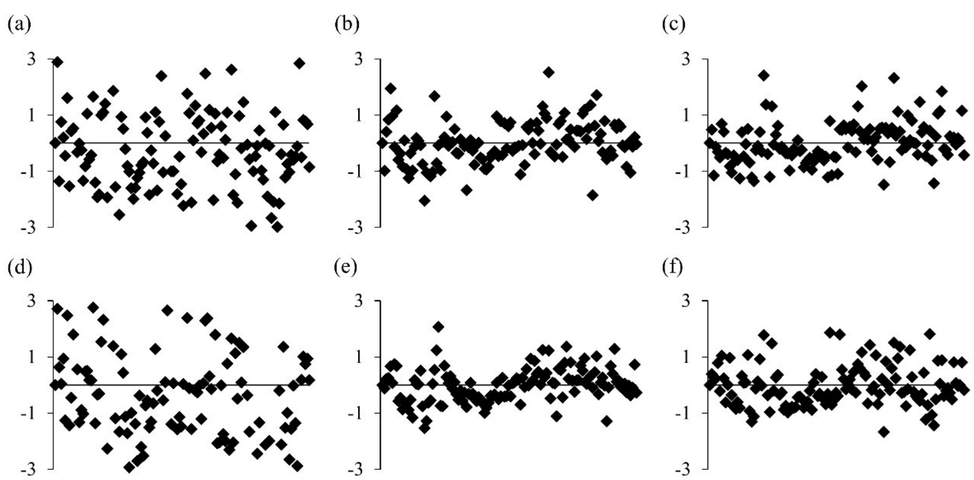

Figure 1. Distribution of standardized residuals of the equations adjusted for estimating fuel load variables: a) residuals of the best equation for estimating 1-h live fuel; b) residuals of the best equation for estimating dead grass fuel; c) residuals of the best equation for estimating 1-h dead fuel; d) residuals of the best equation for estimating total live fuel; e) residuals of the best equation for estimating total dead fuel; f) residuals of the best equation for estimating the total fuel load (live and dead)

The least significant values for the coefficient of determination were found in the adjusted equations for estimating live fuels. For the 10-h and 100-h live and dead wood fuel classes, the regression models were not adjusted, since they did not exhibit a significant load.

Relationship between fuel moisture and meteorological variables

Table 3 shows the results of the correlation between the moisture estimates of the main fuel classes (predominant in the area) and the local meteorological variables at the time of collection, namely ambient temperature (°C) and relative air humidity (%). No significant difference was observed between temperature and humidity for live grass fuel (Lg), total live fuel (Tl), and total fuel.

Table 3. Correlations between the humidity of the fuel classes and air temperature and relative humidity, as obtained during evaluations conducted in the region of Jalapão, Tocantins, Brazil

	Live fuel moisture			**Dead fuel moisture**			
Variable	Lg ($U_{\%}$)	1-h live fuel ($U_{\%}$)	Tl ($U_{\%}$)	Dg ($U_{\%}$)	1-h dead fuel ($U_{\%}$)	Td ($U_{\%}$)	T_{otal} ($U_{\%}$)
Temperature (°C)	-0.001	-0.230**	-0.131	-0.218*	-0.335**	-0.275**	-0.154
Relative humidity (%)	0.250**	0.357**	0.342**	0.389**	0.402**	0.413**	0.370**

Note: Lg (U%) = percent moisture of live grass fuel; 1-h live fuel (U%) = percent moisture of 1-h live fuel; Dg (U%) = percent moisture of dead grass fuel; 1-h dead fuel (U%) = percent moisture of 1-h dead fuel; Tl (U%) = percent moisture of the total live fuel; Td (U%) = percent moisture of the total dead fuel; Total (U%) = percent moisture of the total fuel. * $p < 0.05$; ** $p < 0.01$

Despite the statistical indications in Table 3, the correlations were not significant. Therefore, the humidity of the fuel classes in the campestral Cerrado's phytophysiognomy cannot be explained by instantaneous variation, *i.e.*, by rapid changes between samplings with regard to temperature and relative air humidity, as a function of the short fuel moisture variation range.

Table 4 shows the adjustments of the linear regression models to estimate fuel moisture for different classes as a function of air temperature and relative humidity. In general, the R^2aj values were low and similar, ranging from 0.09 to 0.14.

Fuel consumption

The areas reporting one year without burning did not ignite during the experiment, for a total of 32 sampling units in which fire did not spread, considering plots with 0% consumption.

The fuel consumption values (%) were higher in areas reporting four years without burning for collections performed in the first month of the dry season (May), as well as in areas with two, three, and four years without burning for collections conducted in the last month of the dry season (September).

Table 4. Adjusted regression equations to estimate fuel moisture from relative humidity and air temperature, as obtained during evaluations conducted in the Jalapão region, Tocantins, Brazil

Dependent variable	Regression equations	R²aj	Syx	Syx%
Live grass fuel (U%)	-4.211+(1.477)*AT+(0.601)*RH+ε	0.13	11.19	18.63
1-h live fuel (U%)	69.02+(0.232)*AT+(0.45)*RH+ε	0.09	14.00	15.34
Total live (U%)	32.405+(0.854)*AT+(0.525)*RH+ε	0.12	10.84	14.33
Dead grass fuel (U%)	-1.377+(0.143)*AT+(0.202)*RH+ε	0.11	5.39	55.20
1-h dead fuel (U%)	11.315+(-0.212)*AT+(0.089)*RH+ε	0.14	3.98	49.25
Total dead (U%)	5.766+(-0.053)*AT+(0.14)*RH+ε	0.14	4.14	46.15
Total (U%)	20.517+(0.367)*AT+(0.323)*RH+ε	**0.13**	**7.13**	16.82

Note: AT = air temperature; RH = relative humidity; R^2aj = adjusted coefficient of determination; Syx = standard prediction error; Syx% = percent standard prediction error; ε = model error.

The four principal components were observed when analyzing fuel consumption (Figure 2). Component 1 explained 41.9% of the variation and was best represented by grass height (Htg), dead grass fuel (Dg), dry waste material (Dw), and fuel consumed by fire (Cos). Component 2 explained 21.3% of the variation, represented by litter height (Htl), 1-h dead fuel, and total dead fuel (Td). Component 3, with 11.2%, corresponded to live fuel load variables: live grass fuel (Lg), 1-h live fuel, and total live fuel (Tl). Component 4 explained 9.6% of the variation, represented by the non-destructively obtained fuel variables: number of species (Nsp) and number of individuals (Nin). Inside the boxes, the treatments of the study were identified in the following order: (1) month of fuel collection and (2) years without burning. The fuel collection months were denoted by the following numbers: (1) May, (2) June, (3) August, and (4) September. Burn-free periods were represented by the number of years without burning, ranging from one to four years.

Table 5 presents the adjusted linear regression models for estimating fuel consumption as a function of non-destructive (Htg, Htl, Nsp, and Nin) and destructive (Dg, Lg, 1-h dead fuel, 1-h live fuel, Td, Tl, and total fuel load) variables from the fuel load collected before burning.

Table 5. Adjusted regression equations to estimate percent consumption and dry waste material, based on destructive and non-destructive variables associated with the fuel from the Jalapão region, Tocantins, Brazil

Dependent variable	Regression equations	R²aj	Syx	Syx%
Cos (non-destructive)	-11.763+(3.009)*Htg+(-2.366)*Nin+(18.716)*Htl+ε	0.60	21.92	42.73
Cos (load)	21.594+(35.351)*Dg+(-11.7523)*Lg+ε	0.68	19.81	38.61
Cos (all variables)	14.831+(1.679)*Htg+(-1.381)*Nin+(21.405)*Dg+(-16.881)*Lg+ε	0.74	17.89	34.86
Dw (nondestructive)	0.884+(-0.058)*Htg+(0.469)*Nsp+ε	0.32	1.07	48.91
Dw (load)	2.184+(-1.521)*Dg+(0.348)*Total+ε	0.45	0.96	43.93
Dw (all variables)	0.825+(-0.057)*Htg+(-0.631)*Htl+(0.262)*Nsp+(-0.887)*Dg+(0.505)*Lg+ε	0.53	0.88	40.42

Note: Cos = fuel consumed by fire (%); Dw = dry waste material ($Mg.ha^{-1}$*); Htg = grass height; Htl = litter height; Nsp = number of individuals; Nsp = number of species; Dg = dead grass fuel (*$Mg.ha^{-1}$*); Lg = live grass fuel (*$Mg.ha^{-1}$*); Total = total fuel load (*$Mg.ha^{-1}$*); R^2aj = adjusted coefficient of determination; Syx = standard prediction error; Syx% = percent standard prediction error; ε = model error.*

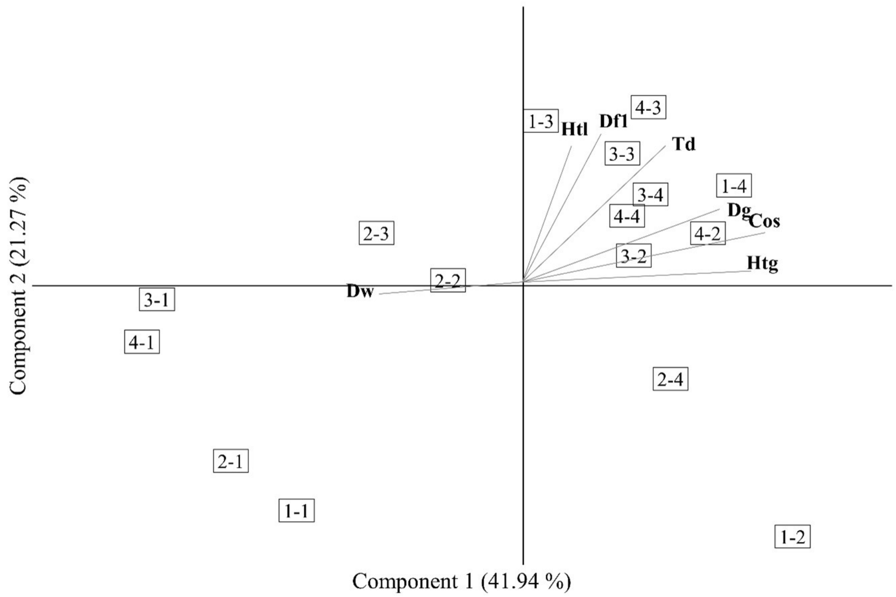

Figure 2. Principal components representation (biplot), considering the consumption of fuel obtained during evaluations conducted in the region of Jalapão, Tocantins, Brazil

Note: Cos = fuel consumed by fire; Dw = dry waste material; Htg = grass height; Htl = litter height; Dg = dead grass fuel; Df1 = 1-h dead fuel; and Td = total dead fuel. The study's treatments are presented inside the boxes in the following order: (1) month of fuel collection and (2) years without burning.

For the percent fuel consumption (Cos), the highest adjusted R^2 value was obtained with the model that considered all variables collected before the fire (both destructive and non-destructive). However, for the dry waste material ($Mg.ha^{-1}$), the adjusted R^2 value was lower than that of the model for estimating consumption, considering that it was adjusted with destructive and non-destructive variables.

DISCUSSION

Linear correlations

By analyzing the relationship between the different surface fuel types and classes (Table 1), low and null correlations were observed between the variables obtained via non-destructive methods and live fuel classes. This behavior is due to the time of collection, *i.e.*, the dry season, when live fuels exhibit their lowest proportions and lower response capabilities regarding variations in indirect factors. An example of this is the null correlation between live grass fuel (Lg) and grass height (Htg).

As for dead fuels, which included fine materials of 1-h live fuel less than 0.7 cm in diameter, as well as dead grass fuel, good correlations with non-destructive characteristics were noted (Table 1). For dead grass fuel (Dg), inverse and significant relationships were observed between the number of individuals and the number of species at the location. That is to say that, as the shading by grassland individuals increases, the total number of individuals and species decreases due to increased competition for light, water, physical space, and nutrients, in addition to certain pioneer species' lower tolerance to shading, preventing the development of new individuals (Parresol *et al.*, 2012; Soares *et al.*, 2017). After the fire has passed, the cycle starts again with an increase in the number of individuals, and, as the biomass of grass individuals increases, the number of individuals and the number of species per area decreases as a result of the aforementioned competition, with the consequent shading of intolerant species. The species in this study belonged to the herbaceous sub-shrub stratum of the Cerrado grassland biome, which is characterized as being predominantly pioneering and intermediate, with little tolerance to shading (Hoffmann *et al.* 2012).

A statistically significant correlation ($p<0.01$) between litter height (Htl) and 1-h dead fuel was observed, corroborating the hypothesis of a relationship between these variables (Table 1). This is because Htl is directly associated with the presence of woody debris and litter. We also noted a significant correlation between Htl, the total amount of fuel, and the total amount of dead fuel. In this regard Souza *et al.* (2002) observed a less significant correlation ($r= 0.60$) between the average height of the needle layer and the 1-h fuel load. Beutling *et al.* (2012) showed a correlation of $r = 0.56$ between 10-h fuel load and litter height. Another significant correlation with a non-destructive characteristic of fuel was that between the dead grass fuel load and grass height, which represents an indirect parameter of the vegetation that can be used to estimate Dg.

Linear regression analysis

The adjusted equations for estimating the fuel load in different classes behaved similarly to the aforementioned correlations, with the highest R^2aj values observed when estimating dead fuels (Table 2). In pine crops in southern Brazil, Beutling *et al.* (2012) obtained R^2aj values of 0.59-0.68 from linear and non-linear equations for estimating the total load. Considering the age of shrub fuel in eucalyptus forests, Gould *et al.* (2011) presented non-linear regression equations with R^2aj values between 0.70 and 0.74 to obtain the fuel load. In pine forests in the United States, Parresol *et al.* (2012) presented R^2aj values ranging from 0.026 to 0.97 for load estimation in different types of fuel, while Battaglia *et al.* (2010), working with mixed coniferous forests, obtained R^2aj values ranging from 0.37 to 0.94 . We noted a scarcity of studies in the Cerrado biome with regard to the adjustment of regression relationships in order to estimate the fuel variables of its campestral phytophysiognomy.

Relationship between fuel moisture and meteorological variables

Despite the lack of studies on the influence of temperature and relative air humidity on changes in the fuel moisture content of the Cerrado, the results presented in this work were not satisfactory, as the regression relationships established to estimate fuel moisture had very low R^2aj values (Table 4). However, in a similar study in southern Brazil in an area with Pinus plantations, Alves *et al.* (2009) tested two different methodologies, one with the plastic basket method and the other with independent samples, obtaining a superior and positive correlation with relative humidity ($r=0.40$ and 0.81) and a higher negative correlation with temperature ($r =-0.45$ and -0.79) than that of this study. Meanwhile, in Taiwan red pine forests, Lin (2004) found values similar to ours while considering temperature ($r=-0.34$) and higher values when considering relative humidity ($r=-0.73$).

Among the few studies with dead grass fuel (buttongrass moorlands), Marsden-Smedley and Catchpole (2001) found higher correlations between temperature and relative humidity (r=-0.78 and 0.82, respectively). In all the aforementioned studies, regression models were built to indirectly estimate the moisture content of the fuel. However, these works consider fuel with more homogeneous characteristics than the surface fuel used in our work, which exhibits considerably heterogeneous and variable characteristics. Thus, our regression equations, adjusted to estimate the moisture content of the fuel, showed low R^2aj values.

The moisture response of the fuels from the Cerrado (Table 3) can be explained by the small variation range of the fuel's moisture conditions in response to temperature and relative humidity changes over short periods (between one collection and another). According to Schroeder and Buck (1970), the moisture content of live and dead fuels has different water retention mechanisms and responses to the environment. According to these authors, herbaceous perennial plants have deep and strong root systems and are less sensitive to short-term changes in temperature and soil surface moisture. Schmidt *et al.* (2017) highlighted that the low intensity of fire in the grassy areas of humid regions in the Cerrado biome (*veredas*), whose soil water availability is high, allows perennial plants to retain high levels of moisture even during the most critical period of the year, *i.e.*, the dry season. The type of fuel used in this work, which mostly belongs to the herbaceous-shrub stratum, was either physiologically active or at least capable of exchanging moisture with the soil through its roots. Therefore, it may have been less able to respond to rapid changes in temperature and relative humidity.

The studies by Lin (2004) and Alves *et al.* (2009) used senescent pine needles deposited in the soil, which no longer engaged in any type of physiological activity. Marsden-Smedley and Catchpole (2001) also performed a study on dead grass vegetation, albeit using a homogeneously distributed species that was typical of the area. Another factor that may have contributed to the low ratios shown in Table 4 may be the heterogeneity of the fuel present in the Cerrado countryside (Castro & Kauffman, 1998), in addition to the different physiological states of the plant material, as discussed above. Despite the small fuel moisture variations in the instantaneous response to weather changes, a longer time frame improves the moisture response. An example of this is the moisture behavior of the fuel from the beginning to the end of the dry season. However, there is a need for further studies on surface fuels from campestral areas to reach more accurate conclusions.

Fuel consumption

Regarding the results of the PCA on fuel consumption, component 1 (Figure 2) showed that the highest consumption (Cos) and the lowest amount of dry waste material (Dw) after burning were closely related to the presence of dead grass fuel (Dg) and to grass height (Htg) in the final months of the dry season (August and September) and in longer periods without burning. The percent rate of consumption and the amount of post-burning dry waste material were in opposite positions, *i.e.*, they behaved inversely. The influences of dead grass fuel, grassland height, and various collection times across periods without burning are demonstrated by the high (positive) values of the representative factors.

The results show a segregation between the dead fuels from the herbaceous layer and the other dead fuel classes, wherein dead grass fuel had a greater influence on fire consumption. These results demonstrate the high flammability of grass fuels in the area (Hoffmann *et al.*, 2012; Santos *et al.*, 2018), which are spatially well-distributed and whose leaves have a high surface-to-volume ratio, facilitating heat absorption (Ganteaume *et al.*, 2013; Molina *et al.*, 2017) and moisture exchange with the environment (Schroeder & Buck, 1970; Dios *et al.*, 2015).

As for the consumption of fuel by fire in the Cerrado, Castro and Kauffman (1998) found higher a consumption in phytophysiognomies related to a greater presence of grass fuel. These authors highlighted that grass fuels were consumed more than others and that the high rates of energy released by fire, along with a more complete combustion, were directly related to the predominance of grass fuel. Therefore, it is important to understand the characteristics of the fuel, which, together with meteorological and topographical conditions, define the severity of a fire and, consequently, the amount of fuel consumed (Ottmar, 2014; Lydersen *et al.*, 2014; Prichard *et al.*, 2014).

CONCLUSIONS

The live fuel classes (live grass fuel, 1-h live fuel, and total live fuel) exhibited non-significant relationships with the fuel variables obtained via non-destructive methods, such as grass height, litter height, and the number of species and individuals.

The significant relationship between non-destructive traits (mainly the ones mentioned above) and the dead fuel classes allowed for the best adjustments of the regression equations for estimating dead fuel loads. In contrast, the weak correlations between the live fuel variables (specifically live grass fuel, 1-h live fuel, and total live fuel) and the non-destructive variables resulted in equations with a low fit.

The relationship between fuel moisture and meteorological variables (temperature and relative air humidity), and thus the adjusted regression equations, showed R^2aj values.

Using data collected in the final months of the dry season, the PCA and the regression analysis demonstrated that the dead grass fuel variables and the grass height of areas with long no-burning periods (more than two years) were the parameters with the greatest influence on fuel consumption by fire.

AUTHOR CONTRIBUTIONS

M.M.S., A.C.B., and M.G., devised the research and project. M.M.S. and A.D.P.S. collected the survey data. E.H.R., A.D.P.S., and M.M.S. were in charge of data processing. M.M.S., G.R.S., and D.B.B. performed and contributed to the data analysis. M.M.S. worked on writing. M.M.S., M.G., and A.C.B. revised the manuscript.

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