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Fire passage on geomorphic fractures in Cerrado: effect on vegetation

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Abstract - Geomorphic fracture is a natural geologic formation that sometimes forms a deep fissure in the rock with the establishment of soil and vegetation. The objective of this work was to analyze vegetation within geomorphic fractures under the effect of wildfire passage. The biometric variables evaluated before and after fire passage were: diameter, height, leaf area index, timber volume, grass biomass, number of trees and shrubs and of species. Results (in fractures) were compared to adjacent areas (control). The effect of wildfire passage on vegetation within geomorphic fractures was not significant because fire followed plant biomass bed and when it met the fracture (wetter), it changed from soil surface to canopy surface (jump fire effect), affecting without significance the number of plants or species; so, fracture could be plants refuge against fire passage. We could infer in our experimental model that quality of plant biomass bed could be more significant than quantity, and microclimate variability recruits plants to the refuge (geomorphic fracture).

Passagem do fogo sobre fraturas geomórficas no Cerrado: efeitos sobre a vegetação

Resumo - A fratura geomórfica é uma formação geológica natural, que em alguns casos forma uma fissura profunda na rocha, com o estabelecimento de solo e vegetação. O objetivo desse trabalho foi analisar a vegetação dentro das fraturas geomórficas sobre o efeito da passagem do fogo. Para isso, as seguintes variáveis biométricas foram avaliadas: diâmetro, altura, índice de área foliar, volume de madeira, biomassa herbácea, número de indivíduos e de espécies arbóreas e arbustivas, antes e depois da passagem do fogo. Esses dados foram comparados com as áreas adjacentes *à*s fraturas (controle). O efeito da passagem do fogo sob a vegetação dentro da fratura geomórfica não foi significativa, pois o fogo seguiu a superfície do solo (cama de fogo formada pela biomassa das plantas) e quando encontrou com a fratura (mais úmida) mudou da superfície do solo para o dossel (pelo efeito de saltar do fogo), afetando não significativamente o número de indivíduos e espécies vegetais; então, a fratura poderia ser um refúgio para as plantas contra a passagem do fogo. Pode-se inferir em nosso modelo experimental de que a qualidade da cama de biomassa vegetal poderia ser mais importante do que a quantidade, e a variabilidade do microclima recruta as plantas para o refúgio (fratura geomórfica).

Introduction

Fire frequency in Cerrado, the common name of Brazilian savanna, is high; annually 25 thousand outbreaks are registered in 2.04 million km^2, 23% of all Brazilian land area. In 2012, 80% of this area burned (Instituto Nacional de Pesquisas Espaciais, 2014). This fire frequency is the result of a long dry period per year, approximately six months without rain (Santana et al., 2010). The registers of fire in this region were dated to 20,000 years before the present in the Late Quaternary period (Salgado-Labouriau et al., 1997), and the effects of fire on Brazilian savanna were widely studied. The fire provides changes of population dynamics, which are formed by individual plants and by species responses to the frequent burning (Hoffmann & Solbrig, 2003; Geiger et al., 2011). It influences the sexual and vegetative reproduction (Hoffmann, 1998), supports the persistence equilibrium model on forest-savanna ecotone (Grady & Hoffmann, 2012), influences the physiological strategies to survive, such as bark thickness of savanna species and the height of reproductive forest species (Hoffmann et al., 2003), prevents recruitment into adult size classes (Medeiros & Miranda, 2008), whereby topkill (Hoffmann et al., 2009), is an important environmental filter, promoting functionality (Silva & Batalha, 2010), and the post-fire recruitment increases the genetic variability of plant species in communities (Andrade & Miranda, 2014).

In this context, in the Brazilian Central Plateau, a region of Brazilian savanna, the geomorphological evolution model produces fractures on rocks and all pedogenesis processes. This evolution followed the steps: i) formation of double surface (After-Gondwana Surface, Medium to Superior Cretaceous), ii) generation of complex lateritic regolith (Surface South-American, Paleocene to Lower Miocene), iii) denudation of lateritic regolith (Lower Miocene), iv) formation of new lateritic face sets (Medium-Miocene to Pliocene), v) dissection of residual surfaces and sedimentation (Superior Pliocene), and vi) rotation of the domain between erosion and pedogenic (Quaternary) (Martins et al., 2004). The last period, with pedogenesis, a consequence of climatic, mineral and biological processes, the deposition of soil occurred on fractures and with this the migration of vegetation by seed dispersion and formation of the seed bank (Duchaufour, 1982). In these fractures soils are deeper than out, with poor drainage, and they generally receive low amounts of sunlight, which results in microclimate (Warren et al., 2013). This distinct environment causes differences in biometric variables of plant population, resulting from water and nutrient availability within fractures (Barbosa et al., 2011).

Most of the literature that studied fire on natural vegetation basically describes four moments: i) the analysis of physical and environmental features (before fire); ii) fire behavior (in the moment of the fire's passage); iii) the analysis of vegetation (before and after fire passage); and the relationship of the fire with plant biomass and microclimate (Hoffmann, 1998; Hoffmann et al., 2003, 2009, 2012; Hoffmann & Solbrig, 2003; Medeiros & Miranda, 2008; Silva & Batalha, 2010; Grady & Hoffmann, 2012; Wotton et al., 2012; Andrade & Miranda, 2014; Parr et al., 2014; and others). This sequence was used in this work to evaluate the hypothesis: the geomorphic fractures could be understood as a refuge in moments of wildfire passage, as they protect the vegetation with a distinct microclimate and a distinct dynamic population (in moments of wildfire passage) in relation to plants out of fracture.

The aim of this work was to analyze the vegetation within geomorphic fractures on the effect of wildfire passage. For this, we evaluated biological and environmental variables, before and after fire passage; fire variables in the moment of fire passage; and we also analyzed the relationship between these variables and we compared the results with adjacent areas (out of geomorphic fractures).

Material and methods

The studying area is located in the Brazilian Central Plateau (Figure 1A), above 1,000 m in altitude (Figure 1B). In this area, geomorphic fractures occur with distinct phytophysiognomies, due to the deposition of soil and to poor drainage (Barbosa, et al., 2011). Out of these fractures occurs a typical phytophysiognomy of Cerrado with 900 ind·ha^{-1} (trees and shrubs with base diameters > 1cm) on Oxisols, and within fractures a typical forest phytophysiognomy with 1,200 ind·ha^{-1} on Entisols, according to Eiten classification (Eiten, 2001). The annual mean rainfall is 1,600 mm, presenting annual mean temperatures of 26 °C. Data was collected in 10 geomorphic fractures and in adjacent areas, as control (out), in sample plots of 0.3 ha each. In total, 6 ha of each delimited area (3 ha "out" and 3 ha "in") were studied. The areas chosen were on slopes below 8º inclination to reduce the influence of slope (Drysdale & Macmillan, 1992).

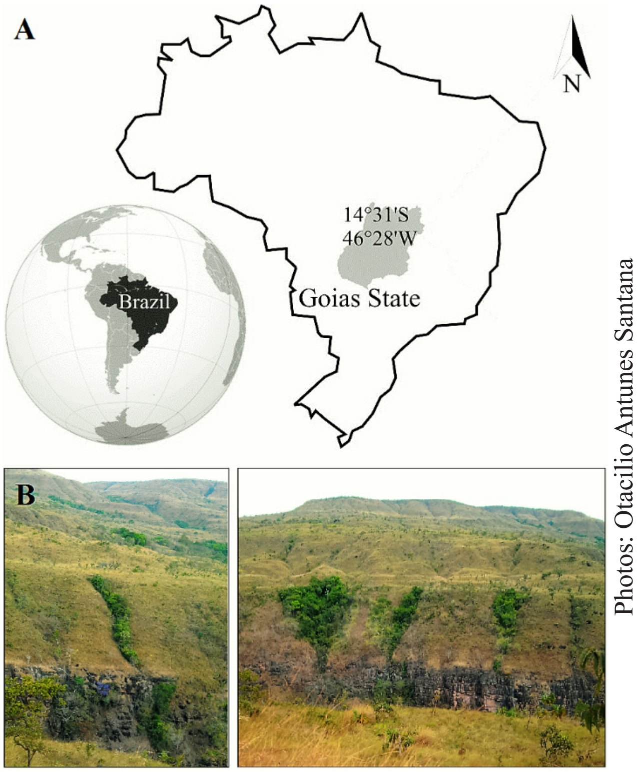

Figure 1. Study area: A) Localization, and B) Cerrado on geomorphic fractures.

The measured variables were: i) fire (height and flame length, temperature of flame, flame speed and fire intensity); ii) environmental (direction and wind speed, water content in soil, water potential in soil, and relative humidity of the air); and iii) biological (number of individuals per ha, diameter, height, leaf area index, total timber volume, grass biomass and the number of species).

The fire related in this work was the wildfire caused by a set of natural factors (as high temperature, low humidity and lightning) and human carelessness (glass and metal wastes and cigarette butts on Cerrado) (Miranda et al., 2009). The fire was not induced directly by man. This study was carried out from March to October of 2014, period that occurred one fire event (September 24, 2014) on an area of approximately 100 ha, with 8-10 h duration (Corpo de Bombeiros Militar, 2014; Instituto Nacional de Pesquisas Espaciais, 2014). The fire variables (height and flame length, temperature of flame, flame speed and fire intensity) were measured during fire passage. The biological variables: number of individuals per hectares, diameter, height, leaf area index, total timber volume, grass biomass and the number of species were measured one time per month, and approximately 24 h after fire passage. In the statistical test, we used data from September 01, 2014 (before of the fire passage) and September 26, 2014 (after of the fire passage). The environmental variables (direction and wind speed, and relative humidity of the air) were measured continuously and we used the mean from March 01, 2014 to September 23, 2014, for statistical analysis between control and in fracture data.

The wind speed and direction was measured with an anemometer (014A-L 3-Cup Anemometer, Campbell Scientific, Logan, USA), and the data was stored in dataloggers (CR200-X series, Campbell Scientific, Logan, USA). The anemometers were fixed 6 m from the ground in ten towers, next to each studied geomorphic fracture at a distance of about 20 m (78m Bardunmast IECII Medium Ice, ENISOLAR Energy Solutions Ltd., Istanbul, Turkey). Another 20 towers were fixed as ten in control treatment and ten in geomorphic fracture. The control treatment towers had 8 m and the in fracture towers had variable heights, according to the depth of fracture and the maximum height of control treatment tower. In these towers, at every 2 m there were thermocouples installed (Type K Chromel/Alumel, Thermometrics Corporation, Northridge, USA) to measure the fire variables (flame height, flame temperature, flame speed and fire intensity) during the passage of the fire. Data were stored in dataloggers (MadgeTech Thermocouple Data Loggers and Recorders, Warner Road, USA).

The relative humidity of the air, before fire passage, was measured with hygrometers (Model MET-2010 Precision Meteorological Thermo-Hygrometer, Yankee Environmental Systems, Turners Falls, USA) sited on the top of towers, and the data was stored in dataloggers (CR200-X series, Campbell Scientific, Logan, USA). Flame length was measured with a camera (Wingscapes® TimelapseCam, EBSCO Industries, Calera, USA) situated on a tower with anemometers. These methods to measure flame variables were performed according to Wotton et al. (2012). All equipment collected and registered data in all time (March to October of 2014).

Soil water content and water potential were also measured (GS1 Ruggedized Soil Moisture Decagon Devices, Pullman, USA) in control treatment and in geomorphic fractures, from the surface to every 0.2 m of depth until 2 m (Figure 2). The data was stored in dataloggers (HOBO Micro Station Data Logger - H21-002, Bourne, USA). We used the mean of all studied depth per treatment to statistical analysis between control and fracture treatments. The water content in soil and water potential in soil variables were measured continuously and took the data from March 01, 2014 to September 23, 2014, for statistical analysis between control and fracture treatments.

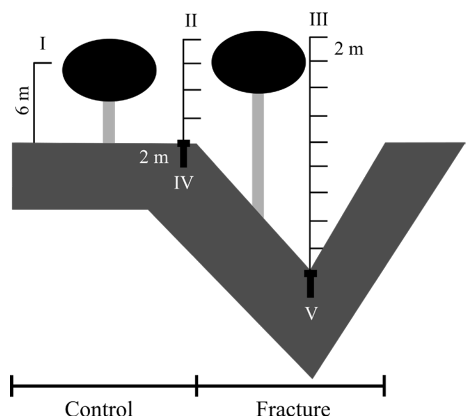

Figure 2. Method scheme. I) Tower with the anemometer. II and III) Towers with thermocouples and hygrometer sensors in each 2 m of height. IV and V) Soil water content measurer with a sensor to each 0.2 m of depth.

All trees and shrubs (> 1 cm in diameter at base) were counted (number of individuals per ha and of species) in the study area. Species identification was performed in IBGE herbarium (Brazilian Institute of Geography and Statistics) according to APG III (The Angiosperm Phylogeny Group, 2009). The diameters were sampled with Digitech Professional Gator Eyes (Clinometer, Haglof, Långsele, Sweden), and height was inspected with a Vertex IV (Haglof, Långsele, Sweden). Leaf area index (LAI) was estimated with LAI-2200C Plant Canopy Analyzer (Li-Cor, Lincoln, USA) measured to 1.3 m of height. Grass, green biomass (Poaceae + Cyperaceae) and total timber volumes were measured with an Industrial 3D Scanner (3D scanner – KDLS – DK – FK – four Lens, Foshan, China), in 1 m² plot with 100 repeated random samples in each delimited area. The plant variables were constantly measured (each month) before (beginning from March 01, 2014), and soon after of the fire passage (approximately 24 h).

Data were normally distributed ($p > 0.05$; $K^2 = \chi^2$) (D'Agostino et al., 1990). T-tests between control and fracture treatments data were carried out to calculate p-value (95% confidence interval) in all variables: height and length of flame, the water content in soil, the temperature of flame, the water potential of soil, flame speed, relative humidity of the air, and fire intensity. χ^2 tests were performed to determine p-value between the times before and after classes distribution (diameter, height, and individual timber volume).

Multiple regression analysis was carried out between fire intensity ($\hat{Y}_i$) and the variables: water content in the soil (X_1), relative humidity of the air (X_2), total timber volume (X_3), LAI ($\cdot$ ha^{-1}) (X_4) and grass biomass (X_5) to calculate the coefficient of determination (R^2) with and without the independent variables, the p-value of the independent variable (ANOVA pre-test), equation (full model), and error of adjust (ε). The theoric model was $\hat{Y}_i = a + \beta_1 \cdot X_1 + \beta_2 \cdot X_2 + \beta_3 \cdot X_3 + \beta_4 \cdot X_4 + \beta_5 \cdot X_5 + \varepsilon$, and the regression model was calculated using the MIXED procedure of SAS (SAS Institute Inc., Cary, NC, USA, version 9.2). All data set was checked about required statistical assumptions, mainly the possible multicollinearity between the independent variables tested by Farrar-Glauber test (Farrar & Glauber 1967). The model was improved according to Akaike information criteria (Akaike, 1998). Pearson Correlation (r) was performed to analyze the interaction between fire intensity and the independent variables in each treatment group (Zar, 1999).

Results

The results of soil variables and relative humidity of the air showed a significant difference (all $p < 0.001$) between the two delimited sample groups (Figure 3). Within geomorphic fractures, the microclimate is wetter than the control treatment as observed by variables of the water content in the soil, water potential of the soil and the relative humidity of the air. We could infer on distinct fire behavior between the sample groups (all $p < 0.001$) from these results associated with the wind speed registered by the towers. Flame height in relation to surface of out the fractures, flame temperature, flame speed and fire intensity were highest out of fracture than in the geomorphic fractures (Figure 3). Only the variable length of the flame was lowest out of fracture than in the geomorphic fractures.

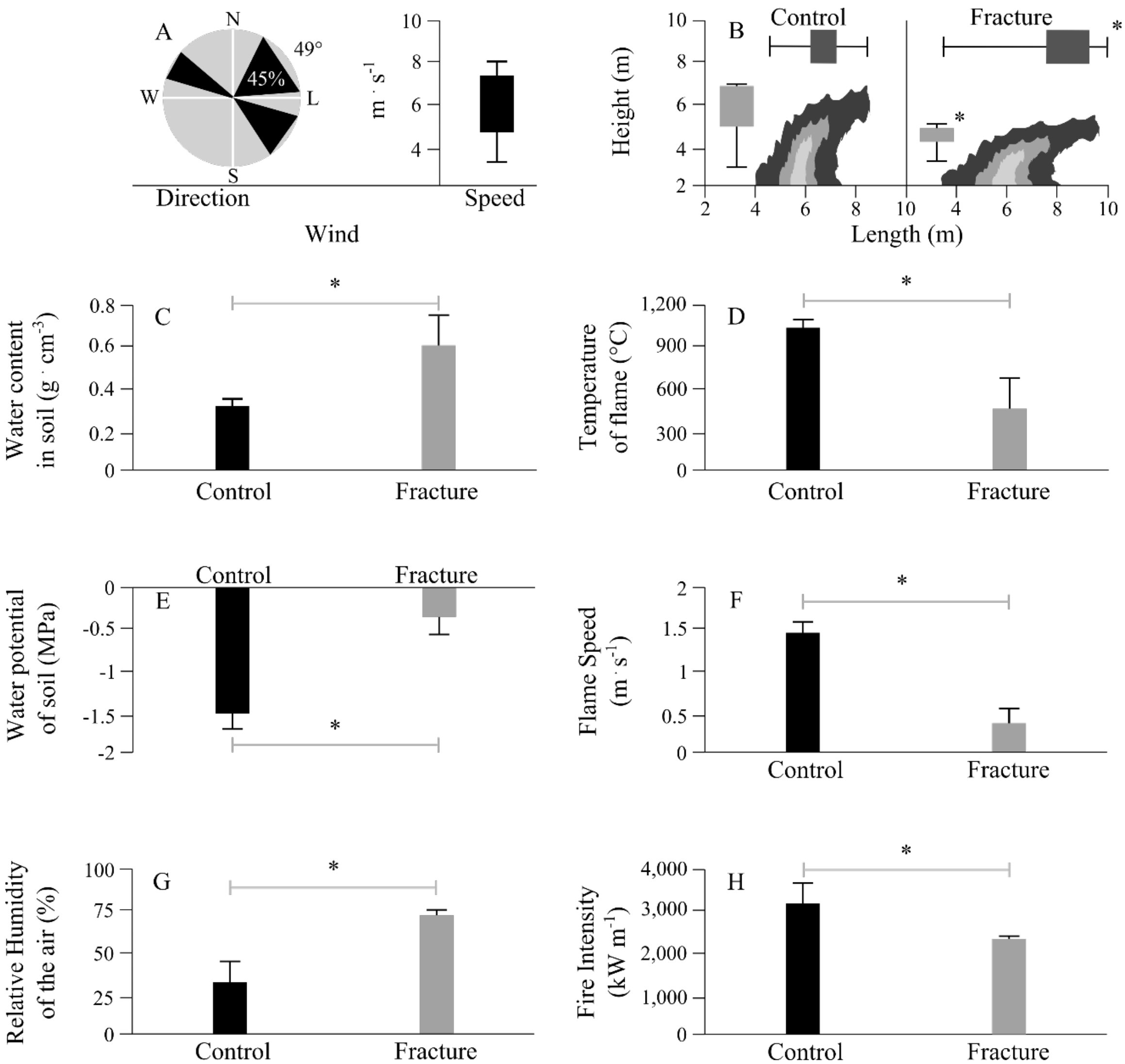

Figure 3. Results of microclimate, fire behavior and soil variables. Wind variables (A): direction and speed; flame variables: height and length (B), temperature (D), speed (F) and intensity (H); soil variables: water content (C) and water potential E); and relative humidity of the air (G). All variables (except wind variables) in control treatment and in geomorphic fractures. * $p < 0.001$

Out of geomorphic fractures (control treatment), all plant variables resulted in significant differences ($p < 0.001$) when compared after fire passage (Figure 4). These differences were not detected when these variables were compared within fractures ($p > 0.05$). The number of trees and shrubs per ha and grass biomass per ha reduced significantly on control areas when measured soon after the fire. These could have reflected in values of number of species and in diameter class distribution, height, and total timber volume. In control treatment class distribution changed ($p < 0.001$) from inverted "J" curve to normal distribution. To height and timber volume data, the number of individuals in the first diameter classes were reduced ($p < 0.001$). These differences were not detected in vegetation data distribution measured within fractures ($p > 0.05$). Leaf area index per ha also had a significant reduction after the fire passage in control treatment ($p < 0.001$).

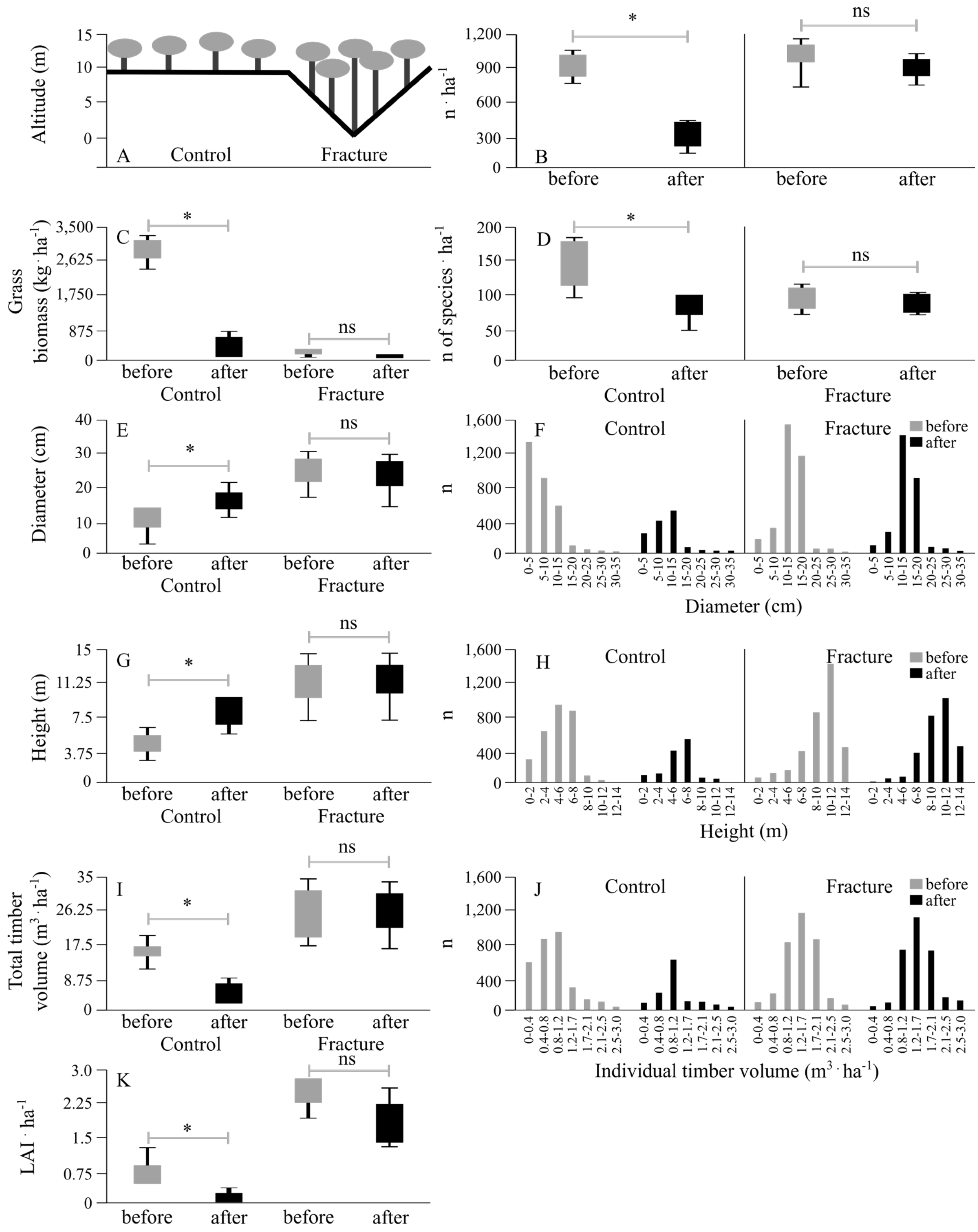

Figure 4. Results of plant data. Mean of height (A), number of individuals per ha (B), diameter (C) and diameter classes (D), height (E) and height classes (F), total timber volume (G) and total timber volume classes (H), grass biomass (I), number of species (J) and leaf area index per ha (K; LAI ha^{-1}), before and after the fire, in control and geomorphic fractures treatments. * $p < 0.001$ and ns $p > 0.05$

With these results, we could infer that exist the inverse relationship between microclimates and plant biomass values with fire behavior values (fire intensity, r > -0.700, Figure 5, Table 1), and these could be evidenced in the two delimited areas. Grass biomass values were the ones that presented direct relationship with fire intensity values (r = 0.926). At the same time, flame height values (in the relation of towers) was highest within fractures due to the depth of fracture and by the high presence of plant biomass (mainly total timber volume and LAI). Another cause of the highest height of fire was the lowest registered temperature in the fracture than that registered in control treatment. This result was a reaction of fire to the opposite side with low values of water content, e.g. low relative humidity of the air. The relationship of fire intensity with microclimate was more strong and inverse (r > -0.830) than with plant biomass variables (r > -0.700).

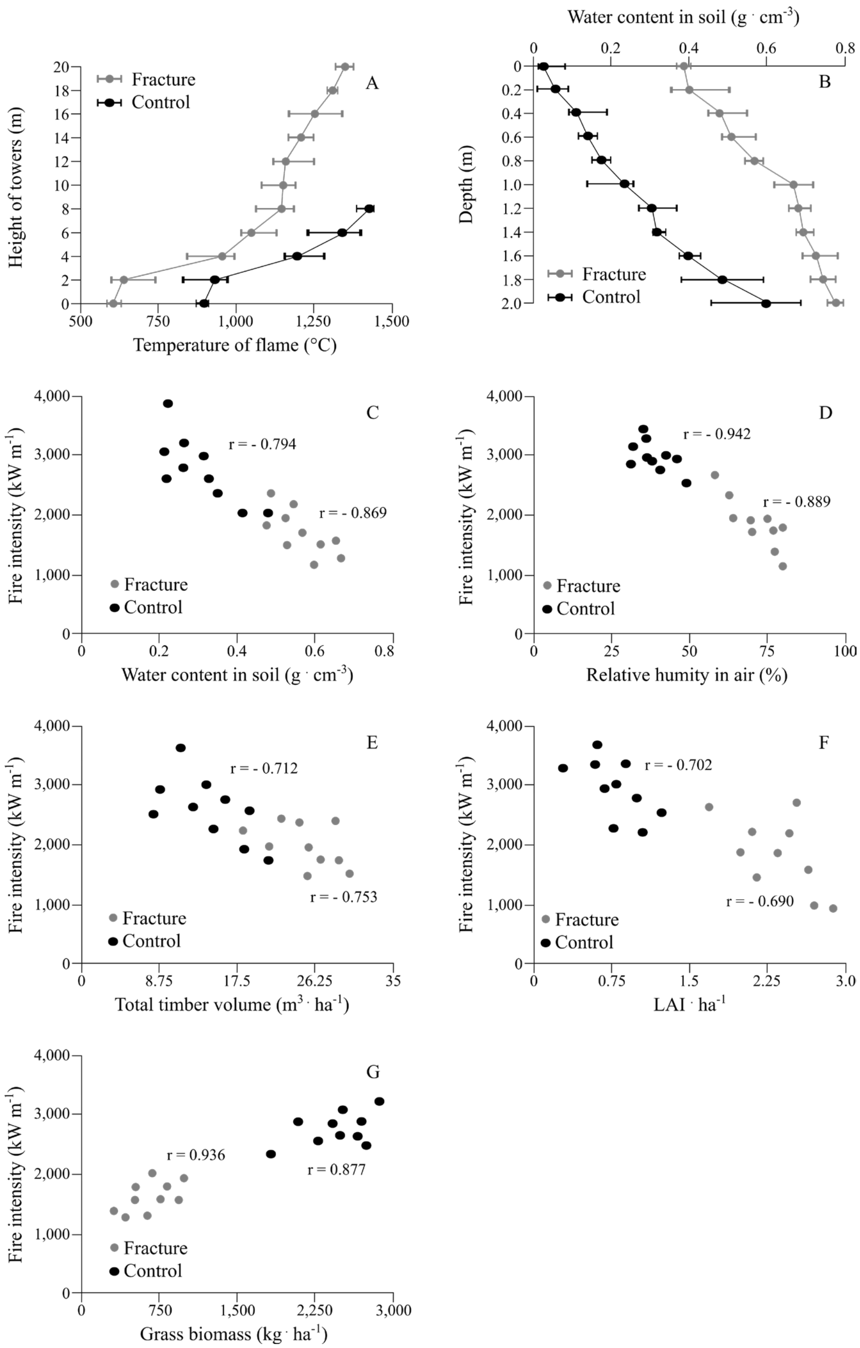

Figure 5. Relationship between height of towers and flame temperature (A); depth and water content in the soil (B); and fire intensity with water content in soil (C), relative humidity of the air (D), total timber volume (E), leaf area index per ha (F), and grass biomass (G). r = Pearson correlation.

Table 1. Results of multiple regression analysis and Pearson correlation (r).

Independent variables	β value	p value	R^2 without independent variable	ε	r
Water content in the soil	-3333.3	< 0.001	0.77	0.011	-0.830
Relative humidity of the air	-23.2	< 0.001	0.73	0.014	-0.920
Total timber volume	-83.3	< 0.001	0.80	0.009	-0.735
Leaf area index ($LAI \cdot ha^{-1}$)	-666.7	< 0.001	0.81	0.016	-0.701
Grass biomass	-0.53	< 0.001	0.84	0.023	0.926
All variables (full model)*	-	< 0.001	0.87	0.074	

The results of multiple regression analysis showed that all variables were significant to the full model ($p < 0.001$). The multicollinearity between the independent variables was not found in the adjusted model ($p > 0.800$). The decreasing sequence of the variable significance of for the adjusted model was (Table 1): relative humidity of the air (RHA) > water content in the soil (WCS) > total timber volume (TTV) > leaf area index (LAI) > grass biomass (GB). With the presence of environmental variables, the adjust was better to model ($R^2 > 0.80$) than only with plant variables ($R^2 < 0.75$). The error of adjusting was smaller than 1%, and the generated equation with the coefficients of regression was as presented in equation 1.

$$FI = 16895.2 - 3333.3WCS - 23.2RHA - 83.3TTV - 666.7LAI - 0.53GB\ (\pm 0.084)$$

where: FI = fire intensity ($kW\ m^{-1}$), WCS = water content in the soil ($g\ cm^{-3}$), RHA = relative humidity of the air (%), TTV = total timber volume ($m^3\ ha^{-1}$), LAI = leaf area index ($LAI\ ha^{-1}$), GB = grass biomass ($kg\ ha^{-1}$).

In the field, the direct observation and registers were used to verify the fire passage on geomorphic fractures (Figure 6). The fire intensity value reduced on the fracture. This data could evidence that the geomorphic site could be a refuge for individual plants and species.

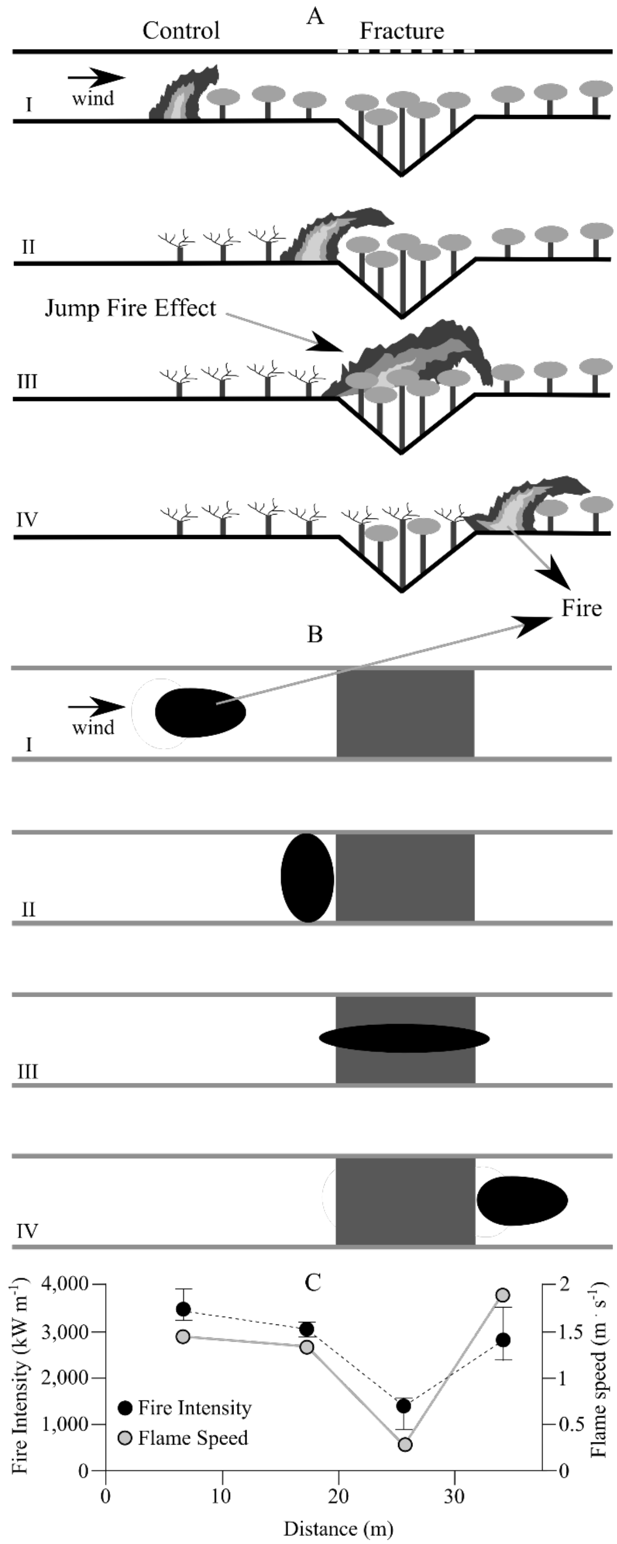

Figure 6. Geomorphic fracture protecting the vegetation (from I to IV = fire passage). Horizontal (A) and up (B) view. Distinct fire intensity and flame speed on its passage (C).

Discussion

Variables results observed in this work were within value range presented in other works that used similar sampling method in regions with the same phyto-physiognomy (Table 2). The environmental and biological data showed high variability according to literature from the studied region (Oliveira & Marquis, 2002). Cerrado is a mosaic of physical and environmental features that results in distinct vegetation dynamics and plant population distributions (Eiten, 2001; Hoffmann & Moreira, 2002). In this mosaic system, studies described that fire is important to maintain equilibrium among individuals, affecting seed germination (Andrade & Miranda, 2014), reducing monodominance of species (Hoffmann & Moreira, 2002), and altering herbivory damage to plants (Mistry, 1998; Lopes & Vasconcelos, 2011), that result in maintenance of diversity (Hoffmann & Moreira, 2002; Miranda et al., 2009).

Table 2. Value range of each studied variable in this work and in the literature that used similar methods for the same phytophysiognomy.

Variables	Value range (This work)	Value range (Literature)	References
Wind speed ($m \cdot s^{-1}$)	3 - 8	0 - 12	Santana & Encinas (2013)
Water content in the soil ($g \cdot cm^{-3}$)	0 - 0.8	0 - 1.2	Santana et al. (2010)
Water potential of the Soil (MPa)	-1.75 - 0	-2 - 0	Santana et al. (2010)
Relative humidity of the air (%)	10 - 75	9 - 100	Santana et al. (2010)
Flame height (m)	1 - 7	0 - 12	Liedloff & Smith (2010)
Flame length (m)	3 - 10	1 - 15	Liedloff & Smith (2010)
Flame temperature (ºC)	300 - 1,100	200 - 1,300	Sow et al. (2013)
Flame speed ($m \cdot s^{-1}$)	0.5 - 1.6	0.1 - 3	Sow et al. (2013)
Fire intensity ($kW \cdot m^{-1}$)	1,000 - 3,900	500 - 5,000	Sow et al. (2013)
Individuals (number ha^{-1})	150 - 1,100	50 - 2,000	Santana & Encinas (2010)
Species (number ha^{-1})	50 - 180	40 - 420	Santana & Encinas (2010)
Grass Biomass ($kg \cdot ha^{-1}$)	100 - 3,400	50 - 4,000	Santana et al. (2010)
Diameter (cm): trees and shrubs	4 - 35	1 - 60	Paula et al. (2009)
Height (m): trees and shrubs	1 - 15	1 - 21	Encinas et al. (2009; 2011)
Total timber volume ($m^3 \cdot ha^{-1}$)	2 - 35	1 - 57	Santana et al. (2013)
LAI · ha^{-1}: trees and shrubs	0.2 - 2.9	0.1 - 3.2	Santana & Encinas (2011)

The fire passage reduced the number of individuals on first classes of diameter, height and total timber volume only in control treatment. The grass biomass and leaf area index (LAI) also had reduced values with fire passage on areas out of the fractures. This significant reduction could evidence primarily the fragility of shrubs and grass in relation to fire passage (Parr et al., 2014), mainly in inter-fluvial areas of Cerrado (as out of fractures) (Hoffmann et al., 2012), and secondly the geomorphic fracture protected these reductions. The number of individuals and the number of species did not reduce their values inside fractures, as well as grass biomass, diameter, height, total timber volume and LAI. The significant difference of the evaluated microclimate and water presence in the environment (water content in the soil, water potential of the soil and relative humidity of the air) between areas could be the main factor for these distinct results due to different fire behavior in each case, according to Ripley & Archibold (1999) and Bigelow & North (2012).

The flame had more volume, temperature, speed and intensity out of the fractures than inside. These results evidenced the drier environment out of the fractures, and the presence of a more flammable fuel, as greater density of shrubs and grass (Shafizadeh et al., 1977; Hoffmann et al., 2012). The inside fracture had more fuel (timber and tree leaf) but with lower inflammability (Shafizadeh et al., 1977), associated with a higher humidity of the environment. In the studied areas, the fuel quantity could not determinate the significant changes in the fire passage. Moisture on formed plant biomass (fuel beds) could be the main factor. When the fire passed into the fracture, its intensity and velocity were reduced, causing a lower impact on vegetation by reducing the contact and enhancing the height in relation to the soil. This event could be denominated as 'jump fire effect' (Figure 5) when fire changes from the 'fuel bed' site to continue its route of passage (Viegas et al., 2013; Raposo et al., 2014).

Thus, microclimate could influence the quality of 'fuel' (wetter) and 'fuel bed' could determine the fire intensity and flame speed, influencing the vegetation (Figure 5). This corroborates with the results of multiple regression analysis where fracture influenced the environmental variables, that influenced the biological variables, that influenced on fire passage. The fracture could serve to modify the fuel bed to surface of canopy, carrying out a jump effect of the flame. This movement could favor the implantation of plant refuge and habitats that promote individuals and survival of species for longer times against the passage of fire (Knapp, 2015).

Conclusion

The effect of wildfire passage on vegetation within geomorphic fractures was not significant as it was observed that fire follows plant biomass with driest 'fuel bed' when meeting the fracture (wetter). The fire changed its 'fuel bed' from surface of the soil to surface of the canopy (jump fire effect) and it did not affect the number of plants and of species.

So, inside fractures could be considered a refuge of plants against fire passage. We could infer in our experimental model that quality of plants biomass bed could be more significant than quantity, and microclimate variability recruits plants to the refuge (geomorphic fracture).

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