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Spatial analysis of fire and its relationship with landscape configuration in the Cerrado

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ABSTRACT

Fire is a natural disturbance in the Cerrado (Brazilian savanna) but its effects on the landscape can alter its patterns of severity and frequency, endangering some areas of the biome such as in Sempre Vivas National Park in the state of Minas Gerais. We spatially analyzed the fire regime in areas of Cerrado vegetation during the years 2003 and 2017 according to to severity and the influence of the spatial configuration of the area. We used pre- and post-fire Landsat satellite images to calculate the change in the normalized burn index (dNBR) to analyze fire severity per year. We then used fire scar metrics to analyze the relationship between fire severity and the spatial configuration of the landscape. Fire-scar severity was low, probably due to the density and structure of typical Cerrado vegetation and to variation in annual precipitation. Although a significant relationship was found only between fire severity and the patch density landscape metric, the results showed variation in the landscape configuration of burned areas.

Key words: Fire severity; Cerrado; Landscape metric.

Análise espacial do fogo e sua relação com a configuração da paisagem no Cerrado

R E S U M O

O fogo é uma perturbação natural no Cerrado, mas seus efeitos na paisagem podem alterar seus padrões de severidade e frequência, colocando em risco algumas áreas do bioma, como no Parque Nacional Sempre Vivas, no estado de Minas Gerais. Analisamos espacialmente o regime de fogo em áreas de vegetação de Cerrado durante os anos de 2003 e 2017 de acordo com a severidade e a influência da configuração espacial da área. Usamos imagens de satélite Landsat pré e pós-incêndio para calcular a mudança no índice de queima normalizado (dNBR) e analisar a gravidade do incêndio por ano. Em seguida, utilizamos métricas de cicatrizes de incêndio para analisar a relação entre a gravidade do incêndio e a configuração espacial da paisagem. A severidade das cicatrizes de incêndio foi baixa, provavelmente devido à densidade e estrutura da vegetação típica do Cerrado e à variação na precipitação anual. Embora tenha sido encontrada uma relação significativa apenas entre a severidade do fogo e a métrica de densidade da paisagem, os resultados mostraram variação na configuração da paisagem

Palavras chave: Severidade do fogo; Cerrado; Métricas de paisagem.

Introduction

Fire has been considered the most relevant factor in maintaining the amount of biomass in the various phytophysiognomies of the Cerrado (Brazilian savanna) (de Andrade et al., 2021), and in other kinds of savannas worldwide, despite various environmental factors, such as soil nutrients and water availability, with the capability of influencing vegetation structure (Veldman et al., 2015; Durigan & Ratter, 2016). In addition to the presence of accumulated biomass in a landscape, its spatial arrangement can also be relevant to fire advancement if there are gaps that make heat transfer difficult (Atchley et al., 2021).

The risk and prevention of forest fires can be predicated by their planning and management when founded on spatial and temporal mapping through remote sensing techniques with high potential for monitoring affected vegetation (Jesus et al., 2020). Such analyses involve identifying areas with the most frequent forest fires and quantifying and identifying their changes in time and space to comprehend fire dynamics. (Alvarado et al., 2017).

Changes caused by fire are related to its behavior, which is described by its severity and type (Costa et al., 2023), energy released, vegetation structure and speed of propagation (Gomes et al., 2018; Lima et al., 2020). Spatial factors that influence fire behavior include landscape heterogeneity and the arrangement of its components (Salomão et al., 2018).

The spatial configuration of a landscape involves the arrangement of its components, which has a considerable effect on fire severity and, in the long term, on fire regime (Iglesias et al., 2022). Thus, a landscape can become increasingly fire prone (Tepley et al., 2018).

Each type of vegetation produces different fuel for fire in terms of structure and biomass accumulation (Magalhães et al., 2017). Some phytophysiognomies are more susceptible to fire than others (Veldman et al., 2015), such as savannas versus forests, which reflects the fire regime (Schmidt et al., 2016). In the Cerrado, there is a predominance of fires in herbaceous-shrubby formations (Ribeiro & Walter, 2008), due to fuel accumulation and the disastrous large fires that have occurred therein (Smith et al., 2016).

The average annual high temperature of the Cerrado ranges between 24°C and 28°C while the average annual rainfall reaches up to 2000 mm, with convective activity between November and March and a dry period between May and September. The amount of burned area increases exponentially with the reduced precipitation and increased dry biomass accumulation during the dry period (Alves et al., 2018).

Integrated Fire Management (IFM) is a system used to manage fire in different fire-prone ecosystems (Barradas et al., 2021). However, to ensure the effectiveness of IFM, ecological, cultural and specific management aspects must be considered when proposing the use of controlled burning, as well as fire prevention and combat (Schmidt et al., 2016). As in other savanna ecosystems, fire is a natural disturbance in the Cerrado and is considered a precursor in defining its phytophysiognomies and determining species diversity (Coelho et al., 2018).

As a common practice for fire control and monitoring, IFM contributes greatly to the advancement of scientific research related to the effects of fire in the Cerrado (Borges et al., 2021). Although there is great concern about the effects of fire on the Cerrado plant community, understanding how multiple fires interact to reshape the landscape (Harvey, 2022) becomes just as important.

Post-fire management needs greater attention by studies related to fire in the Cerrado, as it can change the spatial configuration of the landscape, such as the proportion, average size and shape of fragments (Harvey, 2023). These landscape changes support mechanisms of vegetation resilience, such as the extent and diversity of remaining forest patches (Meddens et al., 2018) and the distance to seed sources necessary for post-fire forest recovery (Gill et al., 2022). In this way, effective fire management for the conservation of the Cerrado also includes post-fire monitoring in the landscape, however, there is still little association between the effects of fire on the landscape and the effects of fire on vegetation (Bassett et al., 2017).

This study aimed to evaluate the behavior and effects of fire on the Cerrado ecosystem and how it has contributed to altering the landscape of Parque Nacional das Sempre-Vivas (PNSV; Semper Vivas National Park) in the state of Minas Gerais, Brazil. It also presents a history of increased fire in many regions around the elevated domains of PNSV (Soares et al., 2017). The park is located in the municipality of Diamantina, a region of high historical and cultural importance designated as a UNESCO World Heritage. Since fires are frequent in Cerrado areas of the park, especially during periods of severe drought, this work aimed to identify fire severity in PNSV and its relationship with the spatial configuration of the landscape. The following hypotheses were addressed: 1) the fire regime is capable of changing the configuration of the landscape in PNSV; and 2) the greater the fire severity, the greater the landscape change.

Materials and methods

Study area

The region of PNSV has a tropical humid climate characterized by an annual average temperature of 20 °C, annual average rainfall ranging 1250 – 1500 mm, and a dry period between May and October. The relief is heterogeneous, with slightly undulating fields, several rocky outcrops and mountain ranges (MMA, 2006).

PNSV is located within the Cerrado biome, which has three major vegetation types — forest, savanna, and grassland (Neves et al., 2021). The specific ecosystems analyzed here were rupestrian grassland (campo rupestre) and other savanna formations (Fernandes *et al.,* 2016), both characterized by a mosaic of open vegetation types (Pereira & Fernandes, 2022).

Classification of fire severity

A total of 2,514 burned areas within PNSV were analyzed from 2003 through 2017. The shapes of fire scars by year were made available by PNSV staff. The images were selected and acquired through Instituto Nacional de Pesquisas Espaciais (INPE; National Institute of Spatial Research). Pre-fire images were selected from within a 1 to 3-month period before the first fire of the year while post-fire images were selected from within a 1 to 3-month period after the last fire.

Normalized burn ratios (NBRs; ranging from −1 to +1; Key & Benson, 2006) were calculated for each image and each year (pre-fire and post-fire) using Landsat 5 and 8 ETM+ images of the study area (orbit 180, point 072) taken between 27 July 2003 and 31 December 2017. The difference in normalized burn index [dNBR = 1000 x (pre-fire NBR - post-fire NBR)] was calculated for satellite images, selected before and after fires between the years of 2003 and 2017, using the “raster calculator” tool from ARcGis 10.4 software.

The dNBR values were used to make a PNSV fire severity map in ArcMap software 10.4. Burn scars were located and classified into four categories according to burn severity by average dNBR, as determined by the USGS Firemon Program: i) unburned, ii) low severity burn, iii) moderate severity burn, and iv) high severity burn (Table 1).

Table 1. Classification and description of fire severity categories according to the USGS Firemon Program.

dNBR	Burn Severity	Description
-0.25 a 0.1	Unburned	No evidence of vegetation killed by fire. No charring on tree stems.
0.1 a 0.27	Low severity burn	Ground fire. Herbaceous plants and some shrubs killed. Some charring of tree stems to about 20% of tree height. Less than 25% of trees killed.
0.27 a 0.44	Moderate severity burn	Ground fire and burning of lower tree limbs. Herbaceous plants and some shrubs killed. Stem charring to about 70% of tree height. Between 25% and 75% of trees killed.
0.44 a 0.66	High severity burn	Ground and canopy fire. All shrubs and herbaceous plants killed. More than 75% of stem height charred. More than 75% of trees killed.

The residence time of dry biomass, associated with climatic conditions, determines the size and severity of individual fire events and the dynamics of patches in landscapes (Liu & Wimberly, 2016). Therefore, for this study, rainfall data for the study area was also considered when classifying fire severity for the analyzed scars. Precipitation data for the area was determined using rainfall data from 2006 to 2017 acquired by the Tropical Rainfall Measurement Mission (TRMM) satellite, 343V7 product (Table 2).

Landscape metrics

The spatial configuration of post-fire landscapes was analyzed to determine the effects of fire. Landscape metrics were selected to quantify landscape elements of burned areas (Cerqueira et al., 2021). Four path metrics were used to analyze the configuration of burn scars*: percentage of landscape* (Pland) to analyze the proportion of vegetation cover that escaped or endured the heat of fire (San Miguel et al., 2017); *patch density* (PD) (Walker et al., 2019) to analyze the influence on post-fire resilience of vegetation; *shape* (San-Miguel et al., 2017), to analyze the post-fire total perimeter shape; and *patch area* (PA) (San-Miguel et al., 2017) to analyze the area affected by fire in hectares.

Statistical analysis

Landscape metrics were calculated with Fragstats 3.3 software (Macgarigal et al., 2002). Pearson's correlation coefficients were calculated (R software) between dNBR and landscape path metrics to identify any significant relationship between burn scar configuration and burn severity.

Results

Spatial analysis of fire severity

The fire occurrence series derived from the available shapefile data to characterize the spatio-temporal distribution of fire events in PNSV during the study period revealed a total of 2,514 burn scars, with the highest number in years 2003, 2011 and 2016 (Table 2).

Table 2. Number of burn scars and fire severity classification for PNSV from 2003 through 2017.

	Burned scars		Precipitation		
Year	Number of burned areas	Total burned area (ha)	Collection period	Rainy days	Total (mm)
2003	124	53,550	27/06 – 20/12	37	376
2004	13	28,990	12/06 – 22/12	54	527
2005	32	18,005	02/07 – 23/11	38	396
2006	15	6,875	26/01 – 28/12	153	1878
2007	21	44,991	05/05 – 26/09	9	9
2008	14	7,756	23/05 – 30/10	16	113
2009	5	6,680	26/05 – 17/10	30	137
2010	2	3,998	22/02 – 23/12	96	757
2011	152	86,400	16/05 – 05/09	7	1
2012	0	7,368	21/09/1105/05/13	214	2497
2013	9	0,97	25/08 – 10/09	1	9
2014	118	48,749	22/05 – 15/10	25	79
2015	115	26,417	27/05 – 03/11	24	109
2016	147	31,008	10/03 – 23/12	78	568
2017	6	33,753	01/06 – 31/12	58	457

The frequency distribution of fire severity classes in Cerrado vegetation shows that although 2011 had the largest burned area, most of the burn scars were classified as of low severity (Figure 1). On the other hand, 2016 had the highest number of burn scars classified as of moderate and high severity (Figure 1). The highest peaks of fire frequency were in 2011 and 2016 (Figure 1), while the greatest precipitation was in 2006 and 2012 (Table 2).

Of the total, 1,741 scars were classified as “unburned” and 773 as significant (dNBR above

0.1) with ratings of low, moderate and high severity (Figure 1). The fire severity of burn scars was low for 72.83%, moderate for 20.43% and high for only 7%.

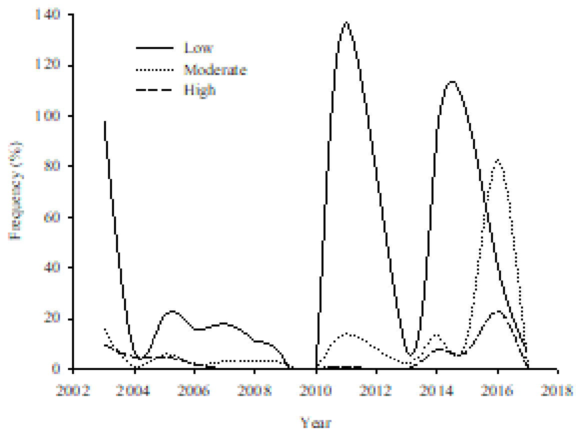

Figure 1. Frequency distribution of fire severity in PNSV from 2003 through 2017.

The spatial distribution of burn scar severity in PNSV is shown in Figure 2. The map represents the spatial distribution of the severity classes for Cerrado areas of PNSV.

Each point was assigned a vegetation and fire severity class based on the USGS Faremon Program classification and vegetation observations made in the field. The Kappa Index for the overall classification accuracy of severity categories was approximately 82.0%.

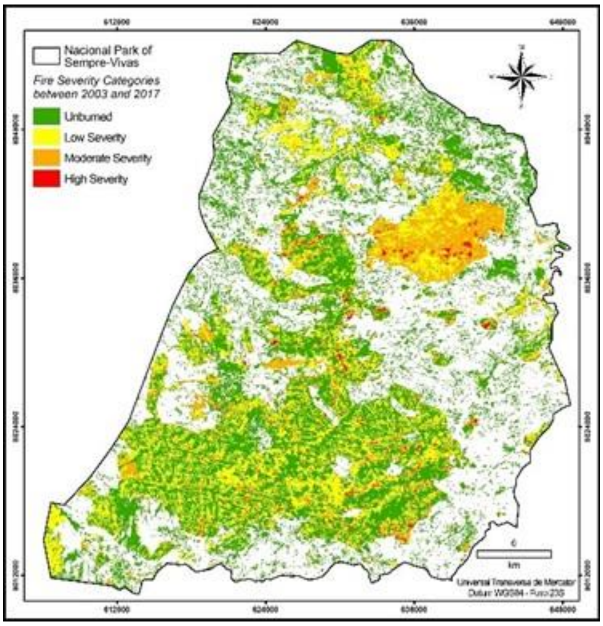

Figure 2. Spatial distribution of burn scar severity in PNSV from 2003 through 2017.

Landscape configuration

Pearson's correlations between fire severity and landscape metrics of burn scars revealed a significant relationship for only patch density (PD; r = -0.13) (Table 3). This indicates that the greater the fire severity, the lower the post-fire patch density, which corroborates the second hypothesis addressed in this study.

Although a significant relationship was not found between fire severity and the other landscape metrics, the results are consistent with the first hypothesis of variation in the landscape configuration of burned areas.

Table 3. Pearson's correlations between ΔNBR and burn scar metrics.

	ΔNBR	Area_ha	Pland	PD	Area_AM	Shape
PA	-0.008					
Pland	-0.007	-0.017				
PD	-0.126**	0.024	0.416**			
Shape	-0.035	0.170**	0.071	0.050	0.064	1.000

** *p < 0.01.*

The results for the burn scar metric *patch area* indicates that fire severity did not influence scar size. Excluding 2003, all burn scars, regardless of severity class, were less than 2 hectares in size (log10) (Figure 3a).

The *percentage of landscape* metric was not related to fire severity. However, there was a significant relationship between *percentage of landscape* and fire frequency. The years 2003, 2011 and 2016 had both the lowest *percentage of landscape* (below zero) and the highest number of burn scars. Years 2009 and 2013 had higher *percentage of landscape* and the fewest burn scars (Figure 3b).

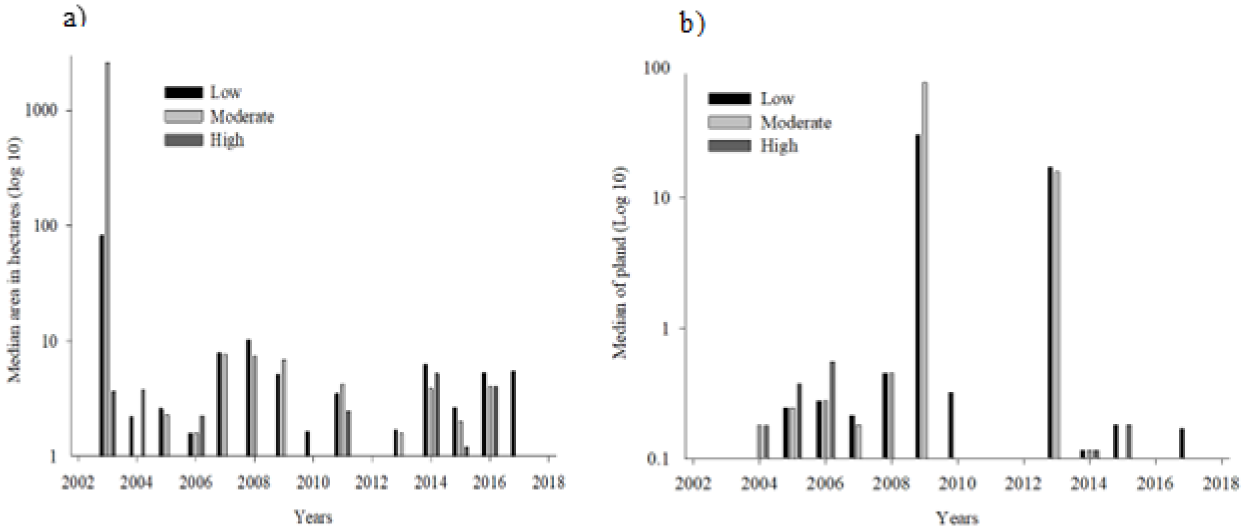

Figure 3. (a) Relationship between fire severity and *patch area* in PNSV from 2003 through 2017. (b) Relationship between fire severity and *percentage of landscape* in PNSV from 2003 through 2017.

Although there was no significant relationship between fire severity and the *shape* metric, the year 2011 had the greatest variation of the high severity class with the closest value to 2 (common logarithm of 100). There was little variation between *shape* and fire severity for the other years, with most burn scars having values less than 1. (Figure 4a). *Shape* metric values between 1 and 2 correspond to more irregularly-shaped burn scars, while values less than 1 correspond to those that are more regularly-shaped, that is, circular (Cerqueira et al., 2021).

Years 2003, 2012 and 2016 had the lowest values for the *patch density* metric (Figure 4b). This result corroborates the Pearson's correlation between fire severity and the *patch density* metric, since 2003 and 2016 had more high-severity burn scars.

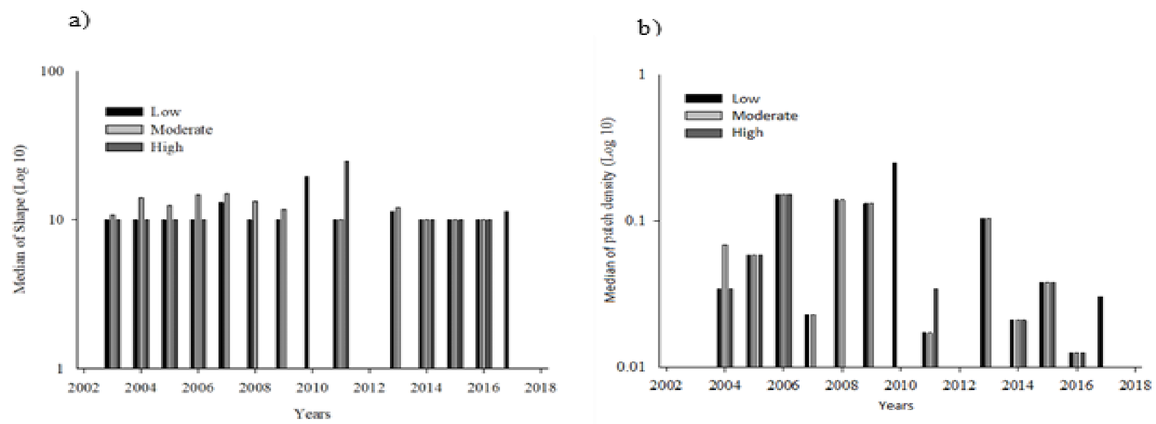

Figure 4. (a) Relationship between fire severity and *shape* in PNSV from 2003 through 2017. (b) Relationship between fire severity and *patch density* in PNSV from 2003 through 2017.

Discussion

The fire regime of PNSV is characterized by low severity due to the density and structure of its vegetation, as shown for the study area. Burn scars occurred in areas of rupestrian grassland/rocky outcrops, where herbaceous-shrubby vegetation predominates with a density of approximately 5% (Ribeiro and Walter, 2008). Areas with sparse and less dense vegetation generate low biomass for fuel and promote greater fire resilience (Landesmann et al., 2021).

Previous studies in Cerrado areas have confirmed the rapid post-fire recovery of its vegetation (Alberton et al., 2023; Fernandes et al., 2021; Le Stradic et al., 2018). Although the vegetation is not very dense, its rapid regeneration may have favored the accumulation of biomass used as fuel in generating the burn scars. Thus, the capacity for rapid regeneration of rupestrian grasslands may have favored post-fire vegetation resilience, resulting in a fire prone landscape.

Studies of the influence of fire severity in rupestrian grasslands (Carmo et al., 2021; Le Stradic et al., 2018; Meira Junior et al., 2019) have indicated that severity is related to fire interval, with increased mean interval having greater severity because accumulated biomass becomes more flammable (Swan et al., 2018). In this way, biomass accumulation can explain the occurrence of fires in the years 2011 and 2016.

Although 2011 showed greater fire spread, occupying 70% of the study area, most of the burn scars were of low severity. The spatio-temporal distribution of fire events reveals that most of the burn scars of 2011 were also burned from 2003 to 2010. This short fire interval, ranging from 6 to 8 months, probably explains the lack of high-severity fires since vegetation does not accumulate sufficient pre-fire biomass. The year 2016 had longer fire intervals, varying from 0 to 8 years, and so biomass accumulation may have favored the occurrence of more severe fires.

The precipitation data also explain why 2011 had the greatest fire spread. A prolonged period of low rainfall between 2007 and 2011 would have been favorable for this occurrence (Batista et al., 2018; Alencar et al., 2015), since large amounts of dry biomass can serve as fuel for large areas of fire during drought years (Santos et al., 2021).

Vertical structural complexity indicates that high fire severity does not depend solely on biomass accumulation for fuel, but also on structural arrangement (Garcia-Llamas et al., 2019). Post-fire biomass accumulation is likely sufficient to support new fires, but vertical fire spread that reaches the canopy layer is influenced by vertical complexity (Penner et al., 2024).

Rupestrian grassland vegetation has low vertical structure since it is mainly characterized by low-density herbaceous-shrubby vegetation in open grassland areas. Thus, the structural composition of rupestrian grasslands may have been a limiting factor for fire severity because it favors the occurrence of low-severity fires in PNSV.

Patch density was the only analyzed metric to be influenced by fire severity. This influence, mainly for high severity scars, did not result in the loss of landscape, as shown by the *percentage of landscape* metric. This is certainly due to the rapid post-fire natural regeneration of vegetation, as discussed above.

The frequent fire regime in PNSV can cause variation in the spatial configuration of the landscape. The results show that the burn scars are numerous and small, resulting in greater fragmentation of the area, in addition to causing reductions in *percentage of landscape* and *patch density* metrics.

Several studies have shown increased landscape fragmentation to be an effect of fire regime (Silva-Junior et al., 2022; Sing et al., 2022; Slattery and Fenner, 2021), while others have shown how fire regime is capable of altering or even creating new mosaics in the landscape and at a variety of spatial scales (Blakey et al., 2021; ChurChill et al., 2021; Halbgewachs et al., 2022).

Fragmentation changes the spatial configuration of forest cover, increasing edge areas and reducing the connectivity of central remnants (Santana et al., 2021; Zhao et al., 2021; Singh and Huang 2022). Even though most of the fire scars of the present study had a regular shape, edge effects are still possible since small fragments are more subject to them due to their greater interaction with the matrix (Slattery & Fenner, 2021).

Fragmentation also makes the landscape more susceptible to fire due to edge effects (Silva-Junior et al; 2022). Edges and small patches present suitable conditions for fire spread, including drier and hotter microclimates, abundant fuel availability, and greater exposure to ignition sources (Santana et al., 2021).

In addition to fragmentation, variation in *percentage of landscape* and reduced density of fragments altered by the fire regime of PNSV are changes that influence landscape heterogeneity and habitat availability, potentially driving patterns of species diversity and community composition (Steel et al., 2021).

Conclusion

Although fires in PNSV are of low severity, they are frequent and can easily be more severe and spread rapidly during drought years and with longer fire intervals. Fire regime has been shown to alter the spatial configuration of the landscape, thereby altering ecosystem heterogeneity. Therefore, fire prevention is necessary, as is management of post-fire areas.

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