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ORIGINAL PAPER

Cerrado physiognomies in a protected area determine the distribution of necrophagous Diptera

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Abstract

The landscape of the Brazilian Cerrado has been modified by human actions in the last decade with a significant increase in fires. Despite efforts to delimit an area for biodiversity conservation, human pressure on the landscape surrounding these units can affect the local environmental condition. We assessed the effect of landscape factors and fire occurrence on necrophagous Diptera diversity in different vegetation physiognomies of the Cerrado region in Chapada das Mesas National Park. We sampled in 35 sites in five physiognomies of the Cerrado biome (Open Forest or *Cerradão*, Dense Woodland, Gallery Forest, Park Woodland, and Woodland) using 350 traps to capture the Diptera specimens. We observed lower dipteran abundance and richness in the Gallery Forest compared to other physiognomies, and the species composition differed from all other physiognomies. Specifically, five species of Diptera were predominantly found in Open Forest or *Cerradão*, two species in Park Woodland, and one in Gallery Forest. The presence of species with generalist habits in forested physiognomies and the low abundance of expected forest-associated species in forest habitats suggests a decline in environmental quality in these areas. This serves as a warning sign for the ecological conditions of the Park's predominantly forested physiognomies.

Implications for insect conservation

Our results highlight that despite the biodiversity of necrophagous dipterans observed in CMNP, ongoing fire frequency and anthropic activities within the park could severely undermine its ability to preserve Diptera biodiversity. Consequently, environmental agencies must intensify monitoring efforts and implement effective measures to mitigate human-induced impacts in this Brazilian Cerrado conservation unit.

Keywords NDVI · Fire frequency · Environmental impacts · Conservation unit · Protected areas management

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Introduction

The Cerrado biome, covering 25% of Brazil's territory, stands as one of the world's most diverse savannas and is considered the second most crucial biome after the Amazon in terms of endemic biodiversity and threatened ecosystems (Durigan and Ratter 2016). It encompasses a wide range of formations and physiognomies, from open fields to dense forests. Notably, 24% of this expanse comprises a mosaic of forest and savannah, with only 4% designated as dry forest (Silva and Bates 2002). This gradient of forest formations can significantly influence the composition and distribution of organisms, including herpetofauna (Nogueira et al. 2005; Barros et al. 2022), insects orders such as Lepidoptera (Pinheiro and Ortiz 1992), dung beetles (Silva et al. 2021), and Diptera (Scherber et al. 2014). For instance, previous studies have documented greater dung beetle richness in savanna areas compared to forest formations (Silva et al. 2021; Barros et al. 2022). The authors suggest that the heterogeneity of habitat within different vegetation formations serves as the primary factor influencing the distribution of organisms across the diverse physiognomies of the Cerrado (Silva et al. 2021).

At present, it is estimated that only 55% (112.6 million hectares) of the native Cerrado coverage remains (Alencar et al. 2020). The primary drivers behind this reduction in coverage are urban expansion, land clearing for agriculture, and cattle ranching (Overbeck et al. 2015). The rapid development of agricultural technology and expansion of cultivated areas, particularly for agro-industrial purposes, have led to significant changes in land use and coverage in the Cerrado. Furthermore, the rates of deforestation, soil erosion, sedimentation, river pollution (Sano et al. 2008), the introduction of exotic plants (grasses), disturbances caused by cattle trampling (soil compaction) (Myers 2006), and increased fire frequency, as fire is used to stimulate grass regrowth for cattle (Ribeiro and Figueira 2011), continue to rise.

Fire is a primary natural disturbance influencing the structure and dynamics of the Cerrado vegetation (Coutinho 1990). Fire occurrences are frequent in savanna-like environments and drive an intricate interplay between climate and vegetation (Miranda et al. 2002). Consequently, the persistent fuel layer is mainly dominated by grasses, which proliferate during the rainy season and become progressively more susceptible to ignition during the dry season, coinciding with the peak of burnings (Van Der Werf et al. 2008). In Brazil, an estimated 3 to 12% of the Cerrado biome is affected by fire annually (Alves and Alvarado 2019). However, human activities have induced uncontrolled, deliberate fires that can severely impact the adaptive capacity and resilience of the region's flora and fauna (Medeiros and Miranda 2008). For instance, fire promotes herbaceous species adapted to annual burning events at the expense of trees (Pivello 2011). This has negative repercussions for tree-associated invertebrates such as bees, wasps and, tree-dwelling species (Peralta et al. 2017; Vasconcelos et al. 2017), as well as larger, more dispersal-capable vertebrates like certain reptiles and amphibians (Sousa et al. 2015; Abom and Schwarzkopf 2016), and even medium and large mammals (Silveira et al. 1999).

The flies of the families Calliphoridae, Mesembrinellidae, and Sarcophagidae are distributed in various environments and have an essential ecological role in the cycling of nutrients by performing organic matter decomposition (Whitworth and Yussef-Vanegas 2019). Studies on the Diptera of these three families provide relevant information on the human influence on flys communities and are essential as indicators of conservation (Sousa et al. 2020) or degradation of natural environments triggered by human activity (Gadelha et al. 2009). Some Calliphoridae species (e.g. *Chrysomya albiceps*) and Sarcophagidae (e.g., *Tricharaea* (*Sarcophagula*) *occidua*) are highly synanthropic (Sousa et al. 2020), while Mesembrinellidae species are non-synanthropic, but is abundant and diverse in tropical rain and cloud forests (Whitworth and Yusseff-Vanegas 2019). Studies with necrophagous dipteran communities in different environments, including the cerrado, have highlighted the influence of vegetation type (Sousa et al. 2016) and anthropogenic activities (Sousa et al. 2020) on patterns of abundance, composition, and richness. Regarding vegetation, communities within more structured and heterogeneous vegetation types had higher species richness than those observed in the less complex zones, with the exception of the sarcophagids in the Amazon Forest (Sousa et al. 2016). Nascimento et al. (2021) recorded that sarcophagids, were more abundant in open areas of Cerrado. These findings are consistent with other research, indicating that sarcophagid species are more abundant in open environments, such as pastures, clearings, and savannas, than in adjacent forests (Sousa et al. 2011, 2016; Yepes-Gaurisas et al. 2013).

The increase in human activity in natural environments makes it necessary to have a biodiversity refuge with available habitat that allows the occurrence of species (Haddad et al. 2015). The consolidation of the Brazilian System of Conservation Units (SNUC) was an important instrument for advancing the protection and preservation of biodiversity and natural habitats and biodiversity conservation (Law nº. 9.985/2000). However, despite efforts to delimit an area for biodiversity conservation, human pressure on the landscape surrounding these units can affect the local environmental condition (Pinheiro and Durigan 2009). In this context, our aim is to assess the effect of landscape factors and fire occurrence on necrophagous Diptera diversity

(Calliphoridae, Mesembrinellidae, and Sarcophagidae) in different vegetation physiognomies of the Cerrado region in Chapada das Mesas National Park (CMNP). We expect that: (a) The environmental factors differ among the five physiognomies of the Cerrado, and that more open formations, such as Park Woodland (PW) and Woodland (WOO), exhibit a higher frequency of fires than forest physiognomies; (b) The patterns of richness, abundance, and composition of necrophagous dipteran species in the CMNP are influenced by the types of vegetation physiognomies in the Cerrado; (c) Necrophagous dipteran species are associated with different physiognomies of the Cerrado, with some species adapted to more open formations (Park Woodland - PW and Woodland - WOO), while others are associated with physiognomies characterized by denser vegetation (Open Forest or *Cerradão* - OF.C, Dense Woodland – DW, and Gallery Forest – GL).

Methods

Study area

This study was carried out in 35 sites situated within the Chapada das Mesas National Park (CMNP) unit conservation, spanning an expanse of 160,046 hectares distributed in the southern state of Maranhão, Brazil (Fig. 1). The topography of CMNP primarily consists of flat to undulating terrain, featuring plateaus at a basal elevation of around 620 m. The climate is classified as tropical wet, with an average annual temperature of 26 °C and yearly precipitation ranging from 1250 to 1500 mm (Souza et al. 2015). There are two well-defined seasons: a dry season from May to October and the wet season from November to April (Carvalho et al. 2023).

The sites were distributed in five physiognomies types of the Cerrado: Open Forest or Cerradão (OF.C, five sites), Dense Woodland (DW, six), Gallery Forest (GF, eight), Park Woodland (PW, six) and Woodland (WOO, 10) (see Ribeiro and Walter 2008 for more details), with a minimum distance of 1 km between sites. Open Forest or *Cerradão* features a forest physiognomy with trees reaching up to 15 m high, creating a continuous canopy without grass (Juhász et al. 2006). It displays xeromorphic characteristics with tree cover ranging from 50 to 90% (Lima-Ribeiro 2008). *Cerradão* soils are typically deep and well-drained, with fertility levels varying from medium to low. They are slightly acidic, classified as Dark Red Latosol, Red Yellow Latosol, or Purple Latosol (Ribeiro and Walter 2008). In Dense Woodland, the vegetation is predominantly arboreal, covering 50–70%, with an average tree height ranging from five to eight meters. The shrubby and herbaceous layers are thinner, likely due to shading caused by the higher tree density. The soil predominantly consists of Purple, Dark-Red, Red-Yellow Latosols, and Cambisols. The Gallery Forest is found along small rivers and streams (up to the third or fourth order), creating enclosed vegetation corridors (galleries) over the watercourse (Roque et al. 2013). The tree layer's average height varies from 20 to 30 m, with overlapping canopies providing tree coverage of 70 to 95%. Park Woodland exhibits savannah formation marked by grouped trees in small, sometimes imperceptible, land elevations called "*murundus*" or "*monchões*". These trees have an average height of three to six meters, forming a tree cover of 5–20%. The soils are hydromorphic, and the *murundus* offer better drainage than the adjacent flat areas (Ribeiro and Walter 2008). Woodland is primarily tree-shrub, with tree coverage ranging from 20 to 50% and an average tree height of three to six meters. It represents a common and intermediate form between Dense Cerrado and Sparse Cerrado, occurring in soils such as Oxissolos Verm Dark-Elho, Red-Yellow, Cambisols, Quartz Sands, Lithologic or Concretionary soils (Ribeiro and Walter 2008).

Environmental factors

The occurrence of fire within various vegetation physiognomies of the Cerrado was determined through the reconstruction of the burning regime within CMNP, achieved by delimiting burn scars. The identification and demarcation of these burn scars were carried out manually through visual interpretation of false color compositions derived from Landsat satellite images spanning a 28-years period (1990 to 2017), which corresponded to the annual burning season between May and November each year. Subsequently, we conducted a comparative analysis between the location of the sampling sites and the documented fire to ascertain the frequency of burning across the sampling sites over the years leading up to the most recent fire event. The burn scars identified within the satellite images were further verified during field sampling.

The Normalized Difference Vegetation Index (NDVI) is derived from the ratio between the difference in reflectance of Near Infrared and Red bands, divided by the sum of the same variables, as illustrated in the following equation: $\text{NDVI} = (\text{NIR} - \text{R}) / (\text{NIR} + \text{R})$ (Eq. 1), wherein NIR signifies Near Infrared and R stands for Red. The resulting values are within the range of -1 to +1, with values closer to +1 indicating higher vegetation density (e.g., Carvalho et al. 2023). Although close to 0, positive values are associated with exposed soil or sparse vegetation, while negative values correspond to water bodies. We calculated the NDVI utilizing a Landsat 8 satellite image captured by the OLI sensor, specifically orbit 222, row 65 of June 2017. These Landsat images were generously provided by the United States

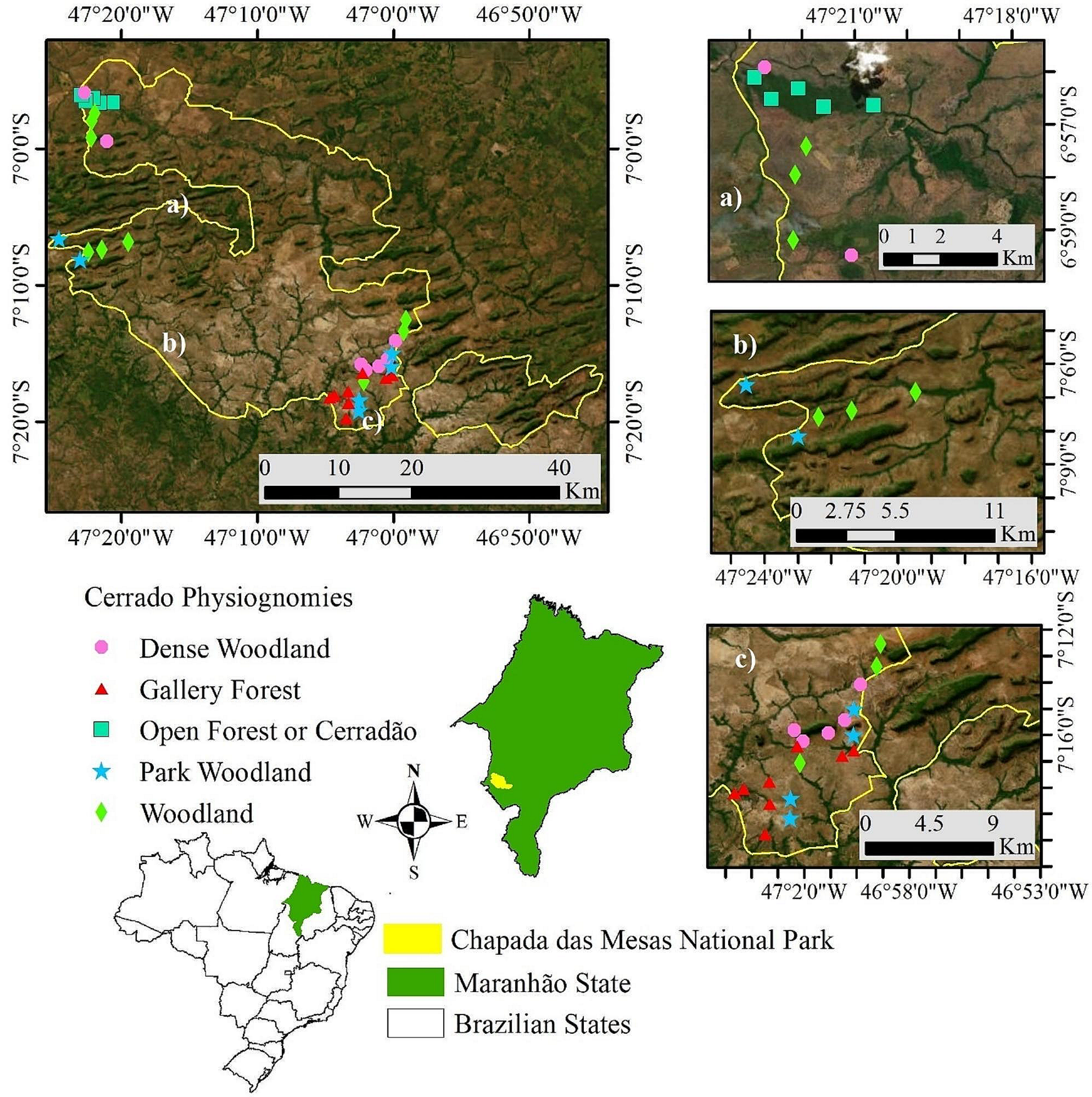


Fig. 1 Geographic locations of the 35 sampled sites within in the Chapada das Mesas National Park (CMNP), Maranhão, Brazil. These sites were strategically positioned across five distinct Cerrado physiognomies: Open Forest or *Cerradão* (OF.C), Dense Woodland (DW), Gallery Forest (GL), Park Woodland (PW) and Woodland (WOO).

Geological Survey (USGS), and are accessible at http://earthexplorer.usgs.gov/. For the calculation, we utilized the image’s 4 band (Red) and 5 (NIR) band, processed using QGIS 3.4.4 software. The classification intervals for NDVI classes were established employing the discrete method of cumulative cut-off and count, resulting in five classes of equal intervals. Additionally, we employed the extract by point procedure, utilizing vectorial data in shapefile format containing sampling points, to extract the pixel values and incorporate them into the attribute table.

We manually assessed the distance between the sampled sites and the pasture areas using the field calculator tool in QGIS 3.4.4. This tool determined the direct distance from a point within the sampled area to the nearest border of a pasture area, providing an estimate of the actual distance between the two areas. The data were projected onto the

UTM system, Zone 23 S, with the SIRGAS 2000 datum. The pasture areas were demarcated through visual interpretation of Landsat 8 satellite images and subsequently validated through field observations. Based on these procedures, four environmental factors were calculated: Distance between the sampled sites and pasture areas (DSPA), Burning frequency (BF), Year of the last fire (YLF) and Normalized Difference Vegetation Index (NDVI). Correlations among these environmental characteristics consistently exhibited low to moderate values (pairwise Pearson correlation r consistently ≤ 0.7, as shown in Supplementary Figure S1), thus allowing for the inclusion of all of them in subsequent analyses.

Biologic sampling

At each site, we employed specific traps adapted by Sousa et al. (2020), each containing 50 g of bovine lung as an attractive bait suspended on tree branches 40 centimeters above the ground. Ten traps were randomly distributed at each site, maintaining a minimum distance of 50 m between them, and a designated separation of 1 km between the replicate sites, totaling 350 traps. The traps were exposed for a period ranging from 24 to 36 h. All fieldwork was conducted during the dry season of October 2015, March and September 2016, April and October 2017, November 2018, and July 2019.

The flies sampled were identified at the species level using the specialized key of Mello (2003), González et al. (2017), Whitworth and Yusseff-Vanegas (2019), Lopes and Tibana (1987), Buenaventura and Pape (2013) and Guimarães (2004). The identification of the Sarcophagidae family is based mainly on the male genitalia, and due to this limitation of taxonomic knowledge, our study identified only male specimens. All individuals are preserved in 70% ethanol and stored in the Laboratory of Environmental Sciences and Biodiversity of the Universidade Estadual do Maranhão, São Luís, Brazil.

Statistical analysis

Each site was considered as an independent sample unit in the analyses. To assess our first hypothesis - The environmental factors differ among the five physiognomies of the Cerrado, and that more open formations, such as Park Woodland (PW) and Woodland (WOO), exhibit a higher frequency of fires than forest physiognomies - we employed Principal Components Analysis (PCA). The PCA utilized Euclidean distance with standardized environmental factors. Axes selected for interpretation were based on the broken-stick criteria (Legendre and Legendre 2012). The significance of the PCA was assessed using Permutational Multivariate Analysis of Variance (PERMANOVA, Anderson 2001), with Euclidean distance and 10,000 permutations. Pairwise comparisons between each pair of Cerrado physiognomies were conducted to interpret the results.

To test our second hypothesis - The patterns of richness, abundance and composition of necrophagous dipteran species in the CMNP are influenced by the types of vegetation physiognomies in the Cerrado - we used the composition, richness, and abundance of species as response variables. Differences in species composition between the physiognomies were assessed using Permutational Multivariate Analysis of Variance (PERMANOVA, Anderson 2001), with pairwise comparisons between each pair of physiognomies. The PERMANOVA analysis utilized Bray-Curtis distance matrix calculated from log-transformed composition data. The null hypothesis of no differences between sites was tested using a Monte Carlo method with 10,000 random permutations, and p-values ≤ 0.05 were considered statistically significant. Principal Coordinates Analysis (PCoA) was employed to visualize differences in species composition among physiognomies. Additionally, differences in species richness of necrophagous Diptera among the physiognomies types were assessed using analysis of variance (ANOVA, Zar 2010), followed by a Tukey's post hoc test. Necrophagous Diptera abundance was analyzed using a Kruskall-Wallis non-parametric test (Zar 2010).

To test our third hypothesis - Necrophagous dipteran species are associated with different physiognomies of the Cerrado, with some species adapted to more open formations (Park Woodland - PW and Woodland - WOO), while others are related to physiognomies characterized by denser vegetation (Open Forest or Cerradão - OF.C, Dense Woodland – DW, and Gallery Forest – GL - we used an Indicator Species Analysis (Dufrêne and Legendre 1997). This analysis calculates an indicator value (IV) for each species, ranging from 0 to 100, based on the relative abundance and frequencies of each species in different physiognomies. An IV of 0 indicates that a species is entirely absent from a specific physiognomy, while an IV of 100 signifies a complete association, where all individuals of a species were exclusively found in a particular physiognomy. The statistical significance of IVs ($\alpha = 0.05$) was tested through 10,000 randomizations of the individuals between sites.

We employed Partial Redundancy Analysis (RDA) and Generalized Linear Models (GLM, Zuur et al. 2009) to assess the relationship between species composition, richness, and abundance of individuals with environmental factors. Prior to conducting the RDA analysis, abundance data underwent a Hellinger transformation (the square root of relative abundance), and environmental factors

Table 1 Results of the principal components analysis (PCA)* and pairwise comparisons of PERMANOVA** for the environmental factors of sites evaluated. significant differences are written in bold

Environmental factors*	PC1	PC2
Distance between sampled sites and pasture areas (DSPA)	0.049	0.978
Burning frequency	-0.891	0.216
Year of the last fire	0.873	-0.136
Normalized Difference Vegetation Index (NDVI)	0.850	0.310
Physiognomies comparisons**	**R^2**	**p.value**
Open Forest or *Cerradão vs.* Dense Woodland	0.132	0.127
Open Forest or *Cerradão vs.* Gallery Forest	0.029	0.660
Open Forest or *Cerradão vs.* Park Woodland	0.151	0.291
Open Forest or*Cerradão vs.*Woodland	**0.322**	**0.026**
Dense Woodland vs. Gallery Forest	0.098	0.251
Dense Woodland vs. Park Woodland	0.101	0.271
Dense Woodlandvs.**Woodland**	**0.266**	**0.012**
Gallery Forest vs. Park Woodland	0.152	0.146
Gallery Forestvs.**Woodland**	**0.347**	**0.010**
Park Woodland vs. Woodland	0.054	0.399

were standardized (Legendre and Gallagher 2001). The statistical significance of the RDA was evaluated using an ANOVA. In the GLM, we used negative binomial adjustment for the richness and abundance of necrophagous flies, and model validated was performed using residuals for adjusted linear mixed models (DHARMa, Hatig 2022). All analyses were conducted in R version 3.4.1 (R Core Team 2016) using the "mgcv" (Wood 2006) and "pairwiseAdonis" (Arbizu 2019) packages for multivariate analyses.

Results

Environmental factors

Environmental conditions varied among the Cerrado vegetation types sampled in our study (pseudo-F = 7.757, $p < 0.01$). In the comparisons, the Woodland (WOO) physiognomy differed from Open Forest or *Cerradão* (OF.C), Dense Woodland (DW), and Gallery Forest (GF) (Table 1; Fig. 2). The areas of Park Woodland (PW) and Woodland (WOO) exhibited a higher frequency of fires, while OF.C and GF showed greater vegetation cover, as represented by the Normalized Difference Vegetation Index (NDVI) (Fig. 3). Furthermore, OF.C and GF had the lowest frequency of fires occurrence, with the last record averaging 21 years ago. The Dense Woodland (DW) physiognomy areas were the most distant from the areas used for pastures (Fig. 2).

Diversity of necrophagous Diptera

We sampled 18,303 necrophagous Diptera individuals distributed in three families and identified 34 species (Table S1). The most abundant species were *Chrysomya albiceps* and *Tricharaea* (*Sarcophagula*) *occidua*. Richness ($F = 5.93$; $p < 0.01$), abundance ($X^2 = 15.02$; $p < 0.01$) and composition (pseudo-$F = 9.97$; $p < 0\ 0.01$) differ among the physiognomies sampled in the study. Considering the abundance, only two physiognomies were different, with Gallery Forest having a lower abundance than Park Woodland (Fig. 4A, Table S2A). Species richness was lower in Gallery Forest than in the other four physiognomies (Open Forest or *Cerradão*, Dense Woodland, Woodland, and Park

Fig. 2 Ordination derived from Principal Component Analysis (PCA) performed of environmental factors of the sites sampled in Chapada das Mesas National Park (CMNP), Maranhão, Brazil. Physiognomies of the Cerrado: *OF.C* = Open Forest or Cerradão; *DW* = Dense Woodland; *GF* = Gallery Forest; *PW* = Park Woodland; *WOO* = Woodland. Environmental factors: *DSPA* = Distance between sampled sites and pasture areas; *BF* = Burning frequency; *YLF* = Year of the last fire; *NDVI* = Normalized Difference Vegetation Index

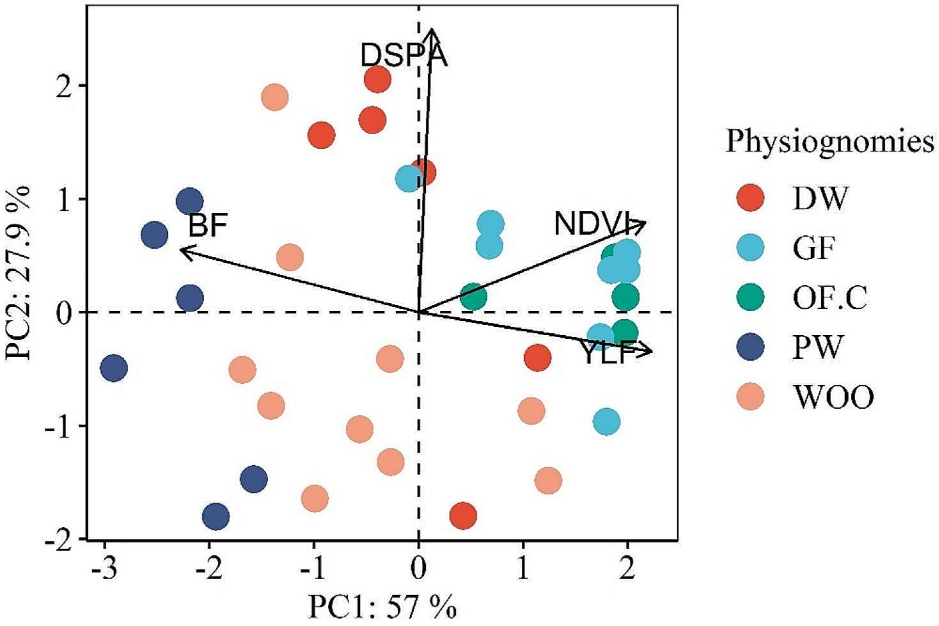
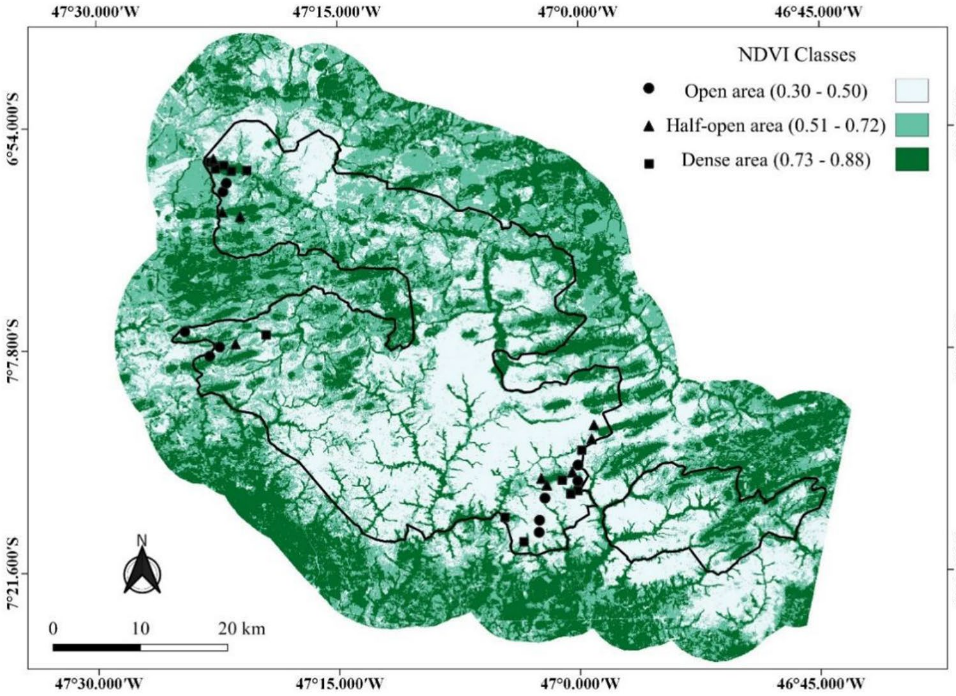


Fig. 3 Spatial distribution of the vegetation index of Chapada das Mesas National Park (CMNP) conservation unit



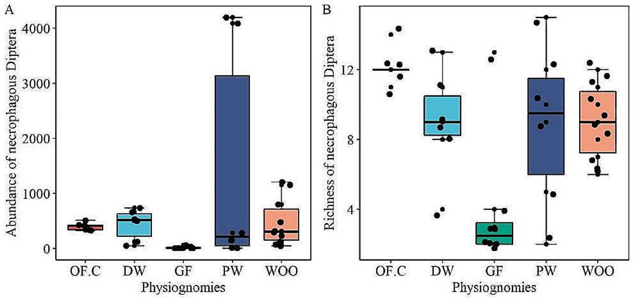


Fig. 4 Box plot of the abundance (**A**) and richness (**B**) of necrophagous Diptera in the Open Forest or *Cerradão* (OF.C) sites, Dense Woodland (DW), Gallery Forest (GF), Park Woodland (PW) and Woodland (WOO). The horizontal line represents the mean; the box represents the interquartile range (IQR), and the whiskers represent values up to +/−1.5×IQR from the 25th and 75th percentiles, respectively

Woodland (Fig. 4B, Table S2B). Environmental factors did not influence the richness and abundance of necrophagous Diptera (Table S4).

The species composition of the Gallery Forest differs from all other physiognomies (Fig. 5). Although the composition of Open Forest or *Cerradão* is similar to Dense Woodland, the species that occur in Open Forest or *Cerradão* differ from Gallery Forest, Park Woodland, and Woodland (Table S3). When evaluating the association of species with the physiognomies of the Cerrado, we observed that *C. albiceps*, *Lucilia eximia*, *Peckia* (*Euboetcheria*) *anguilla*, *Peckia* (*Peckia*) *pexata*, *Peckia* (*Sarcodexia*) *lambens* were associated with Open Forest or *Cerradão* (Table 2). Only *Mesembrinella bicolor* was associated with Gallery Forest and *Oxysarcodexia aura*, and *T. occidua* with Park Woodland (Table 2). Environmental factors were important predictors for species composition of necrophagous Diptera ($F = 4.09$; $p < 0.01$). Two species of Sarcophagidae (*P. pexata* and *P. lambens*) and one species of Calliphoridae (*C. albiceps*), were more associated with the highest values of normalized difference vegetation index (NDVI), year of the last fire (YLF), and Distance between sampled sites and pasture areas (DSPA) (Fig. 5B).

Discussion

Our hypothesis, proposing that environmental factors differ among the five physiognomies of the Cerrado, and that more open formations, such as Park Woodland (PW) and Woodland (WOO), exhibit a higher frequency of fires than forest physiognomies, was corroborated. Fire is a crucial factor in many global ecosystems, influencing the distribution, abundance, and structural form of certain plant species and communities (Bond et al. 2005), as well as animals (Frizzo et al. 2011; Watson et al. 2012; Novoa et al. 2021). In the Cerrado biome, fire, coupled with the seasonality of rainfall and nutrient-poor soils, is considered a determinant of vegetation structure. When the timing and frequency of occurrence define a burning regime, organisms adapt to this disturbance (Miranda et al. 2010). However, the intensity and frequency of fire can play a critical role in transforming the environment (Wu et al. 2015) if it occurs disorderly. Forest physiognomies are less susceptible to natural fires than savannas and grasslands, with Gallery Forests being

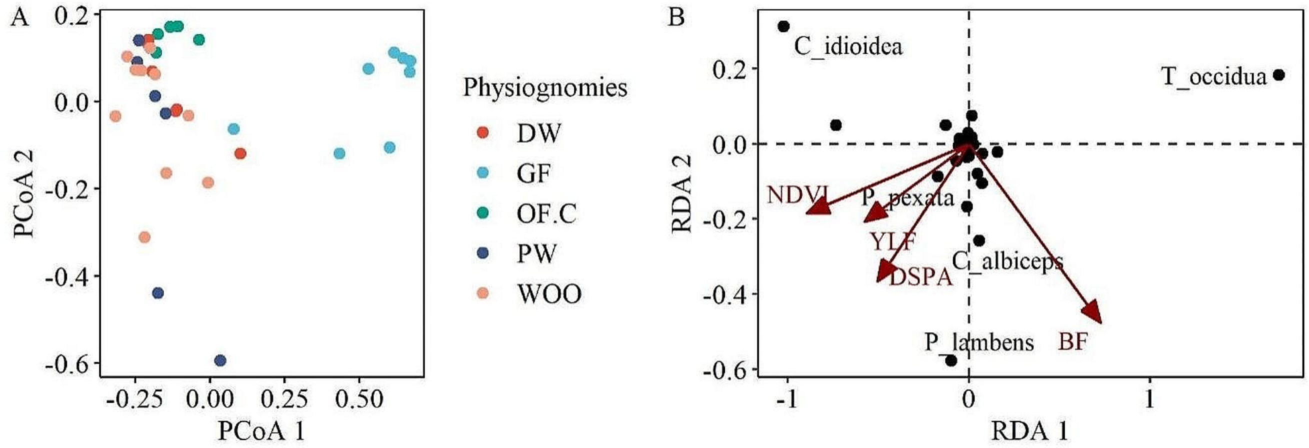


Fig. 5 (**A**) Ordination derived from Principal Coordinates Analysis (PCoA) and (**B**) Redundancy Analysis (RDA) performed of composition species and environmental factors measured in the sites sampled in Chapada das Mesas National Park (CMNP), Maranhão, Brazil. Physiognomies of the Cerrado: *OF.C* = Open Forest or *Cerradão*; *DW* = Dense Woodland; *GF* = Gallery Forest; *PW* = Park Woodland; *WOO* = Woodland. Environmental factors: *BF* = Burning frequency, *NDVI* = Normalized Difference Vegetation Index, *YLF* = Year of the last fire and *DSPA* = Distance between sampled sites and pasture areas

less adapted to fire, followed by Riparian Forests, Dry Forests and *Cerradão*. Thus, while the flora of savannas and grasslands includes numerous species with morphological and physiological characteristics adapted to fire (pyrophytic species), the flora of forests is proportionally less adapted. Nevertheless, the humidity and shading of the forest limit the spread of fire (Walter and Ribeiro 2010).

In the Cerrado biome, the selection pressure to withstand recurrent fires in forest areas was significantly lower than in savannah environments. Consequently, species from forest formations did not need to develop mechanisms to adapt to fire, as many species have efficiently done in savannas and grasslands (Silva et al. 2005). As a result, fire events, whether of natural or anthropic origin, can be devastating for numerous species or their populations when they penetrate forest formations (Silva et al. 2005). Based on our results, we propose continuous monitoring of the fire brigade teams in the Chapada das Mesas National Park, particularly in the Open Forest or *Cerradão* and Gallery Forest physiognomies, as they exhibit the highest vegetation indices (NDVI) and there have been no records of fires on average for 21 years. The occurrence of fire in these physiognomies can pose serious risks to fauna and flora that are not adapted to severe environmental stress caused by fire.

The second hypothesis that the patterns of richness, abundance, and composition of necrophagous dipteran species in the CMNP are influenced by the types of vegetation physiognomies in the Cerrado, was corroborated, as evidenced by differences in richness, abundance and composition between the analyzed physiognomies (Fig. 4). The Cerrado is a highly heterogeneous biome, encompassing forests, pastures and grasslands in the same region (Oliveira and Marquis 2002). Thus, studies on animal communities, such as insects, also reflect the heterogeneity of the Cerrado given their direct susceptibility with vegetation types (Pacheco and Vasconcelos 2012; Mata and Tidon 2013) and regions within the biome (Ferro and Diniz 2007).

The lower richness observed in the Gallery Forest in our study may be attributed to the predominant presence of species from the families Calliphoridae and Sarcophagidae, which generally demonstrate a high degree of adaptation to less forested environments. It is noteworthy that only 8.5% of the total captured species belong to the fly genera *Hemilucilia* Brauer, 1985 (*H. benoisti*, *H. segmentaria*, and *H. semidiaphana*) and *Mesembrinella* (*M. bicolor*). Flies from the genus *Hemilucilia* have been documented in the literature as typical inhabitants of forested areas (D'Almeida & Lopes 1983). In various regions of Brazil, they are consistently associated with forest environments (Sousa et al. 2010, 2016; Esposito et al. 2010; Ferraz et al. 2010). The species *M. bicolor*, along with other mesembrinellids, are considered exclusive to forested habitats, being consistently found only in such areas (Guimarães 1977; Ferreira 1978; Whitworth and Yusseff-Vanegas 2019). The families Calliphoridae and Sarcophagidae include species associated with forest environments as well as more open vegetation, rural, and urban environments (Dufek et al. 2016), suggesting flexibility in the range of niches occupied by these species (e.g., Majer 1987). Studies on Sarcophagidae communities in other locations have shown similar patterns to those found in the CMNP (Sousa et al. 2010, 2011, 2021), indicating that these flies are better adapted to more anthropogenic habitats with reduced vegetation cover. According to Sousa et al. (2011), the resources available in these environments tend to be more ephemeral, implying a competitive advantage

Table 2 Association values, quantified using the indicator value (IV), for necrophagous Diptera species in relation to the Cerrado physiognomies of Open Forest or *Cerradão* (OF.C), Dense Woodland (DW), Gallery Forest (GF), Park Woodland (PW) and Woodland (WOO) physiognomies of the Cerrado. Expressive associations are written in bold

Species	OF.C	DW	GF	PW	WOO	*p*-value
Blaesoxipha (*Gigantotheca*) *stallengi* Townsend, 1917	0.089	0.015	0.000	0.231	0.044	0.211
Chloroprocta idioidea (Robineau-Desvoidy, 1830)	0.264	0.571	0.030	0.010	0.096	0.069
***Chrysomya albiceps*(Wiedemann, 1819)**	**0.454**	0.227	0.000	0.081	0.218	**0.005**
Chrysomya megacephala (Fabricius, 1794)	0.120	0.019	0.000	0.074	0.280	0.177
Chrysomya putoria (Wiedemann, 1818)	0.324	0.000	0.006	0.043	0.062	0.067
Cochliomyia hominivorax (Coquerel, 1858)	0.200	0.000	0.000	0.000	0.000	0.144
Cochliomyia macellaria (Fabricius, 1775)	0.407	0.166	0.000	0.104	0.300	0.078
Helicobia morionella (Aldrich, 1930)	0.000	0.076	0.000	0.000	0.109	0.458
Helicobia pilifera Lopes, 1939	0.000	0.000	0.000	0.000	0.100	1.000
Hemilucilia benoisti Séguy, 1925	0.000	0.000	0.000	0.000	0.100	1.000
Hemilucilia segmentaria (Fabricius, 1805)	0.000	0.000	0.000	0.167	0.000	0.487
Hemilucilia semidiaphana (Rondani, 1850)	0.000	0.283	0.000	0.016	0.006	0.108
Lucilia cuprina (Wiedemann, 1830)	0.000	0.000	0.125	0.000	0.000	0.712
***Lucilia eximia*(Wiedemann, 1819)**	**0.423**	0.132	0.017	0.004	0.048	**0.023**
***Mesembrinella bicolor*(Fabricius, 1805)**	0.139	0.000	**0.672**	0.000	0.000	**0.001**
Oxysarcodexia amorosa (Schiner, 1868)	0.000	0.000	0.000	0.104	0.038	0.649
***Oxysarcodexia aura*(Hall, 1937)**	0.000	0.000	0.000	**0.667**	0.000	**0.001**
Oxysarcodexia avuncular (Lopes, 1933)	0.200	0.000	0.000	0.000	0.000	0.139
Oxysarcodexia carvalhoi Lopes, 1946	0.000	0.000	0.125	0.000	0.000	0.711
Oxysarcodexia modesta Lopes, 1946	0.000	0.000	0.000	0.269	0.039	0.105
Oxysarcodexia oculta Lopes, 1946	0.200	0.000	0.000	0.000	0.000	0.145
Oxysarcodexia parva Lopes, 1946	0.200	0.000	0.000	0.000	0.000	0.143
***Oxysarcodexia thornax*(Walker, 1849)**	**0.503**	0.086	0.000	0.113	0.057	**0.006**
***Peckia*(*Euboettcheria*)*anguilla*(Curran & Walley, 1934)**	**0.381**	0.088	0.012	0.000	0.000	**0.024**
Peckia (*Euboettcheria*) *collusor* (Curran & Walley, 1934)	0.073	0.101	0.019	0.000	0.036	0.805
Peckia (*Pattonella*) *intermutans* (Walker, 1861)	0.284	0.022	0.099	0.000	0.000	0.086
***Peckia*(*Peckia*)*pexata*(Wulp, 1895)**	**0.595**	0.079	0.002	0.034	0.097	**0.001**
***Peckia*(*Sarcodexia*)*lambens*(Wiedemann, 1830)**	**0.425**	0.331	0.003	0.110	0.126	**0.027**
Peckia (*Squamatodes*) *ingens* (Walker, 1849)	0.000	0.167	0.000	0.000	0.000	0.484
Ravinia belforti (Prado & Fonseca, 1932)	0.000	0.230	0.000	0.299	0.083	0.126
Ravinia efrenata (Walker, 1861)	0.000	0.000	0.000	0.167	0.000	0.490
Retrocitomya retrocita (Hall, 1933)	0.000	0.000	0.000	0.000	0.100	1.000
Tricharaea (*Sarcophagula*) *canuta* (Wulp, 1896)	0.000	0.000	0.000	0.000	0.100	1.000
***Tricharaea*(*Sarcophagula*)*occidua*(Fabricius, 1794)**	0.003	0.046	0.000	**0.764**	0.177	**0.012**

for rapidly developing species, such as sarcophagids, which are ovoviviparous.

The environmental factors measured in this study did not appear to influence the richness and abundance of necrophagous dipterans, likely due to the constant activities of fire and grazing in the CMNP over an extended period. Consequently, the species we encountered may have already been filtered by these factors, with the most resistant and potentially sensitive species having become locally extinct. A recent study conducted at CMNP, mapping fire dynamics over 28 years, revealed that the burned area did not change significantly over time (Carvalho et al. 2022). This study also highlighted that despite being a protected area with strict rules governing access and landscape use, there are still human dwellings and cattle raising within the park's boundaries. Moreover, some necrophagous dipteran species exhibit greater adaptive plasticity, enabling them to navigate through a broader range of environmental variations (Mello et al. 2007; Cabrini et al. 2013). However, a study in different phytogeographic regions of Maranhão (Cerrado, Amazon Forest, Palm Forest, flooded fields, and mangroves) demonstrated that other environmental factors associated with microhabitat conditions, such as litter depth, tree/shrub density, vegetation height, and temperature, positively or negatively influenced the patterns of richness and abundance of necrophagous species (Sousa et al. 2021).

The lower species richness contributed to the dissimilarity in species composition of necrophagous Diptera from the gallery forest compared to other Cerrado physiognomies (Fig. 5). A study on necrophagous dipteran assemblages in the Cerrado showed that conserved forests harbor unique dipteran assemblages, characterized by Neotropical species with a more restricted to habitats in forested areas. Conversely, savannas and disturbed forests host more generalist and even exotic species (Mata and Tidon 2013). Furthermore, savannas feature open areas with intense and direct sunlight, generally attracting sarcophagus flies due to their cuticles having high thermal reflectance and their active thermoregulatory behavior (Willmer 1982; Mulieri et al. 2011). The heliophilous characteristic of these flies may provide an adaptive advantage, allowing them to exploit resources in open areas (Dufek et al. 2020).

Our hypothesis that necrophagous dipteran species are associated with different physiognomies of the Cerrado, with some species adapted to more open formations (Park Woodland - PW and Woodland - WOO), while others are associated with physiognomies characterized by denser vegetation (Open Forest or *Cerradão* - OF.C, Dense Woodland – DW, and Gallery Forest – GL), was corroborated. We identified five species associated with Dense Forest or Cerradão, one with Gallery Forest and two with Park Woodland. We observed the association of the species *P. (Peckia) pexata, P. (Sarcodexia) lambens), P. (Euboettcheria) anguila, C. albiceps* and *L. eximia)* with the Open Forest or *Cerradão* physiognomy (Table 2). Due to the generalist habit of these species (Mulieri et al. 2008; Sousa et al. 2021), it was expected that they would be associated with the more open physiognomies of the Cerrado, as already registered in another study (Sousa et al. 2021).

The exotic *C. albiceps* is considered characteristic of anthropogenic environments, such as urban centers (Baumgartner and Greenberg 1984). The native species *L. eximia* is common in forests and rural areas in Brazil (Linhares 1981), Peru (Baumgartner and Greenberg 1984), and Argentina (Mariluis and Schnack 1989). It should be noted that this Open Forest or *Cerradão* physiognomy was the area farthest from the pasture areas, with good vegetation cover, as evidenced by the high NDVI values recorded in the study. Additionally, they also presented the lowest incidence of fire records, with the last record being more than 20 years old. Thus, the association of these species with these environments in the Chapada das Mesas National Park raises a warning sign and concerns regarding the environmental integrity of these areas, as these three species are indicators of anthropic environments, given the preference for open areas (Sousa et al. 2021). The species *O. aura* and *T. occidua* associated with Park Woodland, and *M. bicolor*, linked to the Gallery Forest physiognomy, are consistent with results found in other studies (Mulieri et al. 2011; Sousa et al. 2021). This correlation associates these two Sarcophagidae species with anthropogenic areas and *M. bicolor* with preserved areas.

Our study reveals that more open Cerrado formations, such as Park Woodland (PW) and Woodland (WOO), experience a higher frequency of fires compared to forest formations. We recommend implementing monitoring measures for these physiognomies within Chapada das Mesas National Park (CMNP) to prevent significant environmental damage that could endanger the region's biodiversity conservation efforts. Furthermore, our research demonstrates a relationship between the distribution of some necrophagous species in CMNP and the various Cerrado physiognomies. The presence of species with generalist habits within forested physiognomy, such as Open Forest or *Cerradão*, and the low abundance of expected forest-associated species in forest habitats or at least in Gallery Forests, indicates a decline in environmental quality, serving as a warning sign for the ecological condition of CMNP's predominantly forested areas. Despite the biodiversity of necrophagous dipterans observed in CMNP, continued burning of frequency and anthropic activities within CMNP could seriously compromise the conservation unit's capacity to protect Diptera biodiversity. Therefore, environmental agencies must enhance monitoring efforts and establish effective measures to mitigate human-induced impacts in this Brazilian Cerrado conservation unit.

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Declarations

Conflict of interest All authors declare that there are no conflicts of interest, either financial or not.

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