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Spatiotemporal analysis of wildfires and their relationship with climate and land use in the Gran Chaco and Pantanal ecoregions

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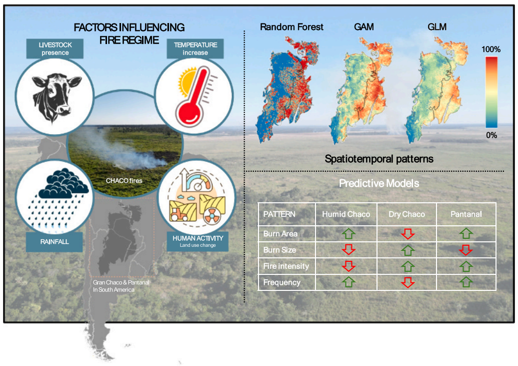
HIGHLIGHTS

- This comprehensive approach assesses fire patterns in the Gran Chaco and Pantanal
- Our approach is based on remote data acquisition and spatiotemporal modelling
- Spatiotemporal patterns indicate an irregular trend in fire activity
- Climate, livestock and tree cover patterns are main drivers of fire activity
- Higher temperatures, lower rainfall, and livestock presence increase fire incidence

GRAPHICAL ABSTRACT



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ABSTRACT

The Gran Chaco and Pantanal ecoregions are the largest remaining dry forest areas in South America. Supporting diverse savanna, woodland and wetland ecosystems, these ecoregions are experiencing rapid changes in land use and fire occurrence with implications for ecosystem integrity. Our study characterizes the spatiotemporal patterns of wildfires in the Gran Chaco and Pantanal, and then examines the relationship between patterns of fire occurrence and climatic and anthropogenic drivers. We evaluated fire data of the last two decades (2001-2020) using the MODIS Collection 6.1 and the Global Fire Atlas products. Results of the fire pattern characterization were then used to model the probability of fire occurrence across each ecoregion (Random Forest, Generalized Linear Model, and Generalized Additive Model).

Our results indicated that most of the total burned area belonged to the Humid Chaco, while the largest individual burned areas were mainly observed in the Pantanal. Fires primarily occurred during the dry season, with the majority of burned areas recorded during this period. Findings from the three modelling approaches consistently illustrated the spatial distribution of fire occurrence, depicting a declining probability of fire

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occurrence from East to West. All models underscored the importance of three variables to predict fire occurrence: temperature, livestock abundance and forest cover. Fire occurrence increased with increasing maximum temperatures and livestock presence and decreased with tree cover. This research helps to clarify the potential consequences of changes in land use, rainfall regime and temperature, and uncontrolled burning practices on the current fire activity in the Gran Chaco and Pantanal ecoregions. Understanding the spatiotemporal patterns of fire occurrence and their relationship with climatic, environmental and anthropogenic drivers can help to design more effective management strategies to mitigate fire impacts and to preserve the ecological integrity of these highly diverse regions

1. Introduction

Fire plays a pivotal role in shaping natural ecosystems worldwide (Bowman et al., 2009; Armenteras and De la Barrera, 2023). The general impacts of fire on vegetation composition, structure, and hydrological cycles are well documented (Morgan et al., 2001; Falk et al., 2007; McLauchlan et al., 2020). To fully understand how these impacts manifest, it is essential to examine the specific dynamics and consequences of fire regimes, including their frequency, size, intensity, and interactions with vegetation and fuel availability (Whelan, 1995; Whitlock et al., 2010; Archibald et al., 2018). Furthermore, fire risk, hazard, and seasonality are critical factors in assessing the broader impacts of fire on ecosystems (Bond and Keeley, 2005; Giglio et al., 2006).

Given changing climatic conditions, fire activity is expected to increase, with extreme events becoming more frequent globally (Flannigan et al., 2006; Bowman et al., 2017; United Nations Environment Programme, 2022). This trend is already evident, with fire being recognized as a major cause of forest loss between 2010 and 2020, particularly in savannas and grassland ecosystems (FAO, 2020). As temperature and aridity increase, especially in fire-prone regions, understanding the specific impacts of these changes on fire dynamics is essential (Eskandari et al., 2020; Butsic et al., 2015; Marchal et al., 2017).

The South American Chaco (Gran Chaco) consists of an extensive semi-arid lowland dry broadleaf tropical forest that supports a diverse assemblage of flora and fauna. It is considered the second largest forested region in South America after the Amazon rainforest (Rodriguez and Morello, 2009; Assine et al., 2016). The Gran Chaco acts as an important corridor connecting species assemblages from the tropical (Amazon) regions and assemblages from the temperate belt (Atlantic forest) regions (Mereles et al., 2020). In addition, it is considered as one of the last extensive dry forest systems on earth (De la Sancha et al., 2021). The Gran Chaco consists of two distinct ecoregions: the Humid Chaco and the Dry Chaco. It is interlinked with the Pantanal, one of the largest protected tropical wetlands globally, where >84 % of the territory is recognized for its high ecological integrity (Libonati et al., 2020). Both aforementioned biomes are biodiversity hotspots that provide unique ecosystem services including critical water and soil resources (Thielen et al., 2021; Guerra et al., 2022).

Anthropogenic activities have significantly altered the natural vegetation in both the Gran Chaco and Pantanal. In the Gran Chaco, large-scale deforestation to enable expansion of agriculture and livestock has led to habitat fragmentation and loss of native species (Gasparri et al., 2008; Mosciaro et al., 2022). Although livestock grazing represents the primary land use across all regions, other economic activities include cultivation of monoculture crops, mostly soybean, sugarcane, wheat and corn (Baumann et al., 2016; Machado and Costa, 2018; Tomas et al., 2019) and also rice in wetter areas of these ecoregions (Laino et al., 2022). Intensive land management often involves the use of fire as an integral part to prepare land for pasture and agriculture, removing undesirable woody vegetation and promoting pasture renovation. Across the area, fire represents a vital disturbance process mediating the balance between grasses, shrubs and woody vegetation, given by complex interactions between factors such as moisture content, soil type and grazing (Delegido et al., 2017; Leal Filho et al., 2021; Vidal-Riveros et al., 2023). The introduction of non-native species and the conversion of land to monoculture plantations have further disrupted the native ecosystems, reducing biodiversity and contributing to modifying fire regimes (Nogueira Junior et al., 2019). In the Pantanal, agricultural expansion, infrastructure development and wetland drainage have degraded natural habitats, increasing the frequency and intensity of fires, especially during drier periods (Marengo et al., 2021; Pott, 2020; Magalhães and Evangelista, 2022).

Although fire is an integral type of disturbance in the Gran Chaco, few studies have examined the specific role of fire in the system (Kunst, 2011). Bravo et al. (2010) explored temporal trends of fire by using tree rings and fire scars in relation to rainfall variability. Previous remote sensing studies have identified different spatiotemporal patterns of fire activity relating to climate, land cover and vegetation at multiple scales (Arganaraz et al., 2015, 2020; Maillard et al., 2022; San Martin et al., 2023). For instance, Correa et al. (2022) assessed the inter-annual variability in fire and land cover changes in the Pantanal between 2000 and 2021 by using the MCD64A1 V.6 product and Landsat LULC data. Naval et al. (2023) used Sentinel 2 imagery to map the 2020 fires and compared the data with historical data from 1987 to 2019, analyzing fire metrics such as number, size and frequency. Moreover, Marengo et al. (2021) used hydroclimatic data to analyze the impacts of the 2019–2020 drought in the Brazilian Pantanal. However, few studies have explored interactions and feedback between fire activity, ecosystem characteristics and the consequences in the Gran Chaco and Pantanal ecoregions. Indeed, recent studies indicate that fire activity in the Pantanal is expected to increase in the near future (Marques et al., 2021; Menezes et al., 2022; Libonati et al., 2022). Furthermore, in recent decades, increased anthropogenic burn frequency in these grassland and savanna environments is changing ecosystem dynamics in ways that are not well understood.

This study seeks to address the scarcity of information on historical patterns of fires, the drivers of fire activity and future projections for fire occurrence in the Gran Chaco and Pantanal. More specifically, we aim to better understand the spatiotemporal patterns of fire occurrence and intensity and how these patterns are related to climatic, environmental and anthropogenic drivers. Given the importance of fire as a disturbance process and the complex interplay between climatic, environmental and anthropogenic factors, we hypothesize that fire occurrence and intensity are strongly influenced by these drivers in the Gran Chaco and Pantanal ecoregions. To test this hypothesis, we analyzed the relationships between fire patterns and potential drivers over the past two decades (2001−2020) using remote sensing data and statistical models. We characterized fire activity—such as fire occurrence, burned area, and intensity—using data from the Fire Information for Resource Management System (FIRMS), MODIS Collection 6.1, and the Global Fire Atlas (GFA). We then explored the links between fire activity and factors like climate, topography, fuel, and land use, employing three statistical models (Random Forest, GAMs, GLMs) to predict fire occurrence in the three ecoregions. This approach enabled us to cross-validate data and gain deeper insights into fire dynamics in the Gran Chaco and Pantanal.

2. Materials and methods

2.1. Study area

This study focuses on the Gran Chaco and Pantanal ecoregions, which are ecologically diverse, fire-prone regions in South America spanning Paraguay, Brazil, Argentina and Bolivia. The study area includes three ecoregions following Dinerstein et al. (2017): the Dry Chaco (793,219 km^2), the Humid Chaco (291,677 km^2) and the Pantanal (170,452 km^2), which together cover a total area of approximately 1,255,348 km^2 (Fig. 1). The Gran Chaco is a vast basin that extends across Argentina, Bolivia, Paraguay and southwestern Brazil (Olson et al., 2001), characterized by a subtropical climate with extreme summer temperatures (> 40 °C) and cool winter temperatures (<-10 °C). Precipitation decreases from east to west, ranging from a maximum of 1500 mm and a minimum of 700 mm (Naumann et al., 2006), and distributed in two clearly differentiated seasons: a dry season (July to September) and a rainy season (October to June) (Arganaraz et al., 2015). The differences in the rainfall regimes define the two clearly distinguished sub regions driven by the water availability gradient: the Humid Chaco and the Dry Chaco. Natural vegetation in the Gran Chaco is a direct result of climate, fire and topography, mainly consisting of a broad mosaic of different formations that includes closed dry forests, open forests, scrublands, and palm savannas (Gasparri et al., 2008). Representative species in the Dry Chaco include *Aspidosperma quebracho-blanco* and *Schinopsis lorentzii*, both of which are known for their fire-resistant characteristics, such as thick bark and deep roots (Prado, 1993; Rodriguez and Morello, 2009). By contrast, the Humid Chaco supports species like *Schinopsis balansae* and *Astronium urundeuva* in elevated areas with deep soils, while *Copernicia alba* appears in areas with greater water availability (Mereles et al., 2020).

In addition to the Humid and Dry Chaco, the study area includes a vast tropical mosaic of wetlands, grasslands and forests called the Pantanal. The Pantanal is located at the NE of the Gran Chaco, extending across the south of the Mato Grosso in Brazil, Bolivia and Paraguay (Evans and Costa, 2013). Known for its high diversity and richness of aquatic, wetland and many terrestrial species, the Pantanal is a large alluvial plain with various ecosystems characterized by periodic flooding. These ecosystems predominantly include savannas with aquatic plants, riparian and dry forests, forest islets, woodlands, grasslands and numerous monodominant formations (Pott, 2020). Representative species in the Pantanal include *Paspalum spp.*, *Cyperus spp.*, *Mimosa spp.*, *Eugenia spp.* and *Tabebuia aurea*, species adapted to survive in the fluctuating water conditions and periodic fires typical of the region (Pott, 2020; Manrique-Pineda et al., 2021).

2.2. Data acquisition and fire regime characterization

To characterize a specific fire regime, several products are currently available for burnt areas, including Global Burnt Area 2000 (GBA, 2000) (Grégoire et al., 2003), L3JRC (Tansey et al., 2008), ATSR Global Burned Forest Mapping (GLOBSCAR) (Simon et al., 2004), Global Land Products for Carbon Model Assimilation (GLOBCARBON) (Plummer et al., 2006), Globfire (Artés et al., 2019), Global Fire Atlas (GFA) (Andela et al., 2019) and the MODIS MCD64A1 Collection 6.1 (MODIS; Giglio et al., 2018). We used GFA in conjunction with the MODIS to characterize fire

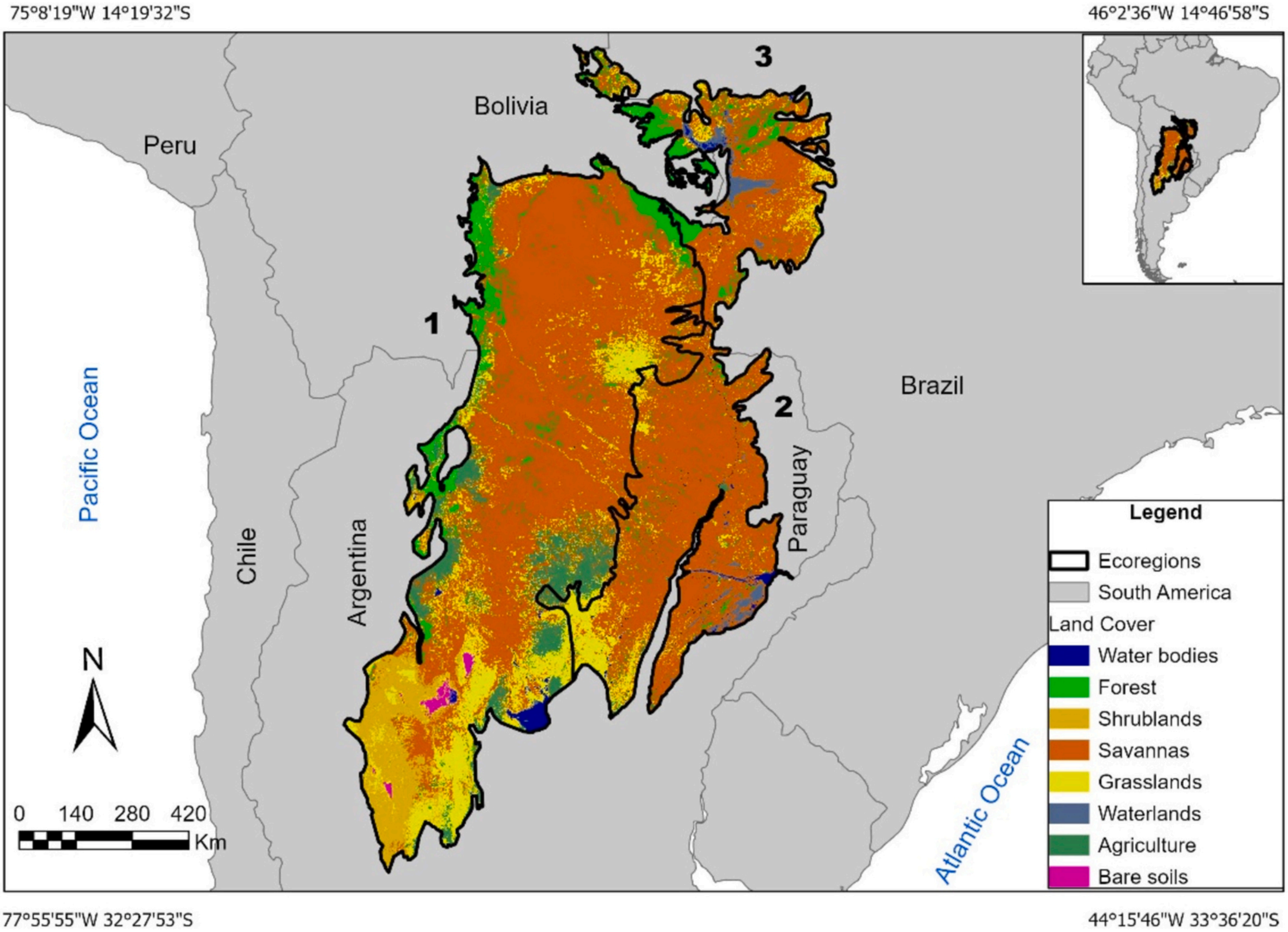

Fig. 1. Map of the study area with land cover types based on MODIS Land Cover Dynamics (MCD12Q1) Version 6.1, derived from the classification of the University of Maryland (UMD). The three studied ecoregions are labelled in black color as follows: 1 Dry Chaco; 2 Humid Chaco and 3 Pantanal.

patterns (Table 1). The GFA is a comprehensive dataset that provides detailed information about the timing, location and progression of individual fires worldwide, based on active fire detection and burned area data from the MODIS sensor. It provides high-resolution data on fire dynamics at the global scale, making it invaluable for fire regime characterization. The GFA dataset is publicly available through NASA's Earth Data platform, providing a crucial resource for fire activity studies. MODIS 6.1 is a monthly product, with spatial and temporal resolutions of 500 m and two days, respectively, and it has been successfully used in previous studies carried out in the region (Arganaraz et al., 2016; Landi et al., 2017; Maillard et al., 2022; Correa et al., 2022). Due to its higher temporal resolution, this dataset is a valuable data source, particularly in tropical conditions where post-fire signals are quickly obscured by sensors, and persistent cloud cover affects image quality (Chuvieco et al., 2018). For consistency, all product layers were projected to the WGS 1984 UTM 21 S coordinate system.

Fire frequency was calculated using GFA for 2003–2016 and the MODIS 6.1 product for the remaining study years (2001, 2002, and 2017–2020). Subsequently, all layers were converted to a binary raster (2.5 km^2 spatial resolution) categorizing 0 as the absence and 1 as the presence of fire. A frequency map (1 to 20) was created by adding all layers using raster; frequencies were then grouped into major categories: 0 (no fire event), 1 (low frequency, 1–2 fire events in the studied period), 2 (medium frequency, 3–4 fire events) and 3 (high frequency; $>$ 4 fire events). This classification was then adapted to reflect local conditions. Fire Radiative Power (FRP) was used as a proxy for fire intensity (Laurent et al., 2018; Silva et al., 2021), with a 70 % confidence level. The zonal statistics tool in ArcGIS PRO 2.9 software was used to obtain an average intensity signal in 6.25 km^2 quadrants.

Similar to previous research (Silva et al., 2021), the burned area was categorized into small ($<$1000 ha), medium (1000–5000 ha) and large ($>$5000 ha) fire scars. Climate seasons were divided according to precipitation (wet and dry) and defined using the date of fire (date of year, DOY) obtained from GFA and MODIS 6.1 products. Monthly and yearly frequencies of occurrence were analyzed to identify patterns during the study period.

2.3. Modelling approach

The relationship between fire activity and potential drivers, including climate, topography, fuel and land use was examined by using three statistical models: Generalized Linear Models (GLM), Generalized Additive Models (GAM), and the decision tree classification algorithm Random Forest (RF), to predict the probability of fire occurrence for the Gran Chaco and Pantanal ecoregions. This combined approach using different statistical models enabled us to infer the spatial probability of fire occurrence (McWethy et al., 2018). These models were selected due to their proven effectiveness in predicting fire occurrence across various regions and their ability to offer distinct perspectives on the factors influencing fire dynamics (Bustillo Sánchez et al., 2021; Rodríguez-Pérez et al., 2020; Sydorenko et al., 2024). Random Forest (RF) is particularly useful for managing complex interactions between variables and has been successfully applied globally, in Mediterranean ecosystems, temperate forests and tropical regions (*e.g.* Rodriguez-Galiano et al., 2012; Eskandari et al., 2020). GLMs (Celebrezze et al., 2024; Beltrán-Marcos et al., 2024) and GAMs (Lindenmayer et al., 2023) complement RF by providing insights into linear and non-linear relationships, respectively. By adopting a multi-model approach, we not only enhance the reliability of our predictions but also provide a comprehensive analysis of the factors influencing fire occurrence. Each model has unique strengths: Random Forest for capturing complex interactions, GLMs for understanding linear relationships and GAMs for modelling non-linear dynamics (Breiman, 2001; Cutler et al., 2007; Dobson and Barnett, 2018; Wood, 2017).

Table 1
Products used to characterize spatiotemporal patterns of fires.

Variable	Format	Unit	Source
Fire intensity	shapefile	Mega wats (MW)	FIRMS
Burnt area (2001, 2002, 2017, 2018, 2019, 2020)	shapefile	Date of year (DOY)	MODIS
Burnt area (2001–2020)	shapefile	Square kilometer (Km2)	GFA

2.4. Statistical analysis

We calculated the total accumulated annual Burned Area (BA) for each ecoregion. To compare the impact of fire occurrence, we also estimated the yearly Normalized Burned Area (NBA) for each of the ecoregions. The NBA is defined as the ratio between the total amount of BA (Ha) in each ecoregion and its respective total area (Ha). The normalization enabled us to account for differences in ecoregion sizes when assessing fire impact. To model the relationship between fire occurrence and human, climate and environmental variables, we used GLM, GAM, and RF. To compare classification categories among the models we used the Kappa statistic (κ), which quantifies the agreement between observed and predicted classifications (values 1 to 0) and it is particularly useful for assessing the accuracy of categorical models and provides a robust measure of model performance (Viera and Garrett, 2005).

The presence/absence of fires was the dependent variable. A set of 8 variables, categorized under topography, climate, fuel composition and land use criteria, was selected as explanatory factors for model input (Table 2). These variables were selected after a comprehensive literature review (Vidal-Riveros et al., 2023) for the study area and on the basis of expert criteria. The GEE platform was used to gather all variables using various algorithms developed for the study area, resulting in the calculation of averages for each variable for the 2001–2020 period. Livestock information for 2010 was sourced from the global product by Gilbert et al. (2018). In all instances, information was retrieved in raster format at a resolution of 1 km^2. Bilinear interpolation was used to rescale fire occurrence (originally at a 2.5 km^2 resolution) to assure consistency in the spatial scale across all variables. The statistical models were derived using R software Version 4.2.2 and Random Forest, Terra and Raster packages.

3. Results

3.1. Characteristics of the fire regime

Within the study period (2001–2020), the largest area was burned in 2020 (11.78 × 10^6 ha) throughout the entire study area, followed by 2002 and 2007 (8.41 and 8.29 × 10^6 ha, respectively) (Fig. 2). The burned area in 2020 was almost twice the mean value for the entire time series (6 × 10^6 ha), accounting for 9.38 % of the area burned. Conversely, the smallest burned area was recorded in 2014 and 2018, affecting 1.98 % and 2.61 % of the study area respectively. Throughout the study period, the burned area fluctuated yearly with no discernible trend. The Humid Chaco contributed on average 40.45 % of the total burned area annually, followed by Dry Chaco (32.92 %) and Pantanal (26.63 %) (Fig. 3 a).

Analysis of the Normalized Burned Area (NBA) revealed that in each ecoregion, on average $>$2 % of the area was burned during the study period (Fig. 3 b). Notably, the NBA for the Pantanal was approximately five times greater than that of the Dry Chaco (10.15 % *vs* 2.39 %) reaching a peak value of 23.71 % in 2020. This year marked the highest recorded NBA for both the Humid Chaco and the Pantanal, while the lowest NBA occurred in 2018 in both ecoregions. In the Dry Chaco the peak of NBA was reached in 2003 (3.33 %), while the lowest rate was recorded in 2018 (1.49 %).

Fires predominantly occurred during the dry season (July to

Table 2
Predictive variables used to model fire drivers.

Variable type	Variable name	Code	Units	Source
Topographic	Elevation	DEM	Meter (m)	NASA ASTER GDEM
Climatic	Vapour pressure Deficit	VPD	Kilo pascal (kpa)	Abatzoglou et al., 2018
	Precipitation	pr	Millimeter (mm)	Abatzoglou et al., 2018
	Max.Temperature	Tmax	Degree Celsius	Abatzoglou et al., 2018
Fuel composition	Net primary production	NPP	kgC/m2/year	MODIS-MOD17A3 (Heinsch et al., 2003)
	Tree cover	TC	Percentage (%)	MODIS-006-MOD44B
	Land Cover	LC	University of Maryland Classification	MODIS-006-MCD12Q1
Land use	Livestock	cattle	Number of animal head	Gilbert et al., 2018

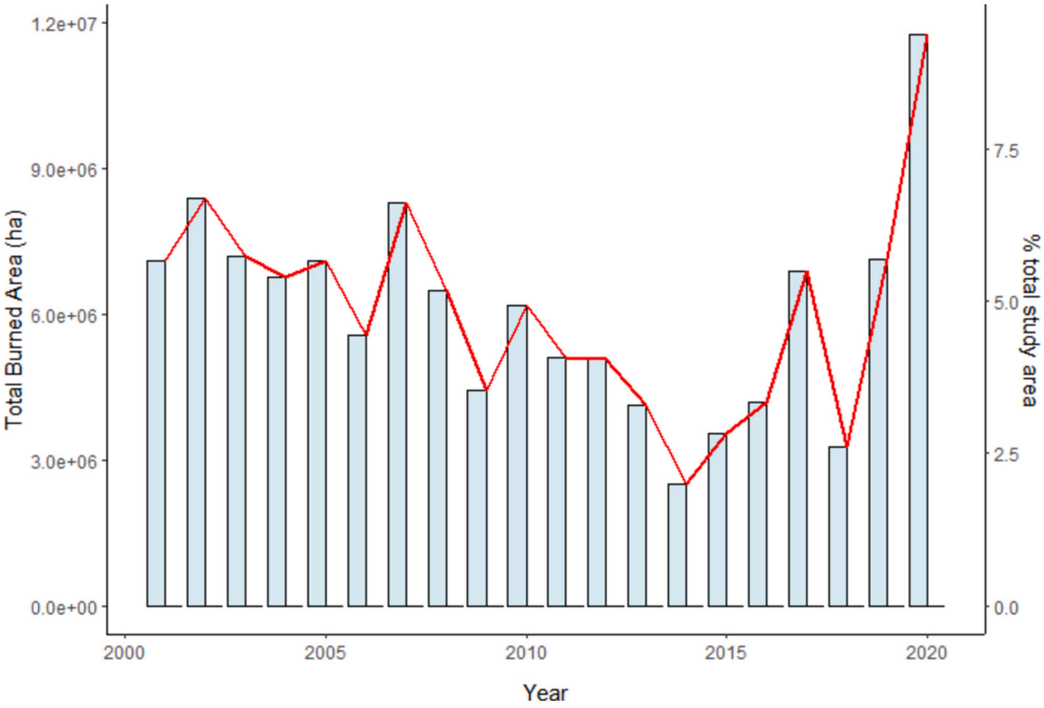

Fig. 2. Total burned area annually across the Gran Chaco and Pantanal: burned area (ha) during the time-span of the study separated by year (left axis in light blue bars) and percentage (%) of total study area burned annually (right axis in red line).

October), with >70 % of annual burned areas recorded during this four-month period (Fig. 3 c). Detailed observation of the patterns of burned area based on ecoregions revealed a slight increase in burned areas during the rainy season (January to March) in the Humid Chaco. On the other hand, an increase in fire patterns was observed in October and November in the Dry Chaco.

Considering the spatial distribution of fire scars, small fires (<1000 ha) accounted for 61.48 % of the total burned area during the study period, with medium (1000–5000 ha) and large fires (>5000 ha) representing 21.78 % and 16.74 %, respectively. Small and medium sizes were more prevalent in the Humid Chaco, while large fires occurred more frequently in the Pantanal (Fig. 4). The study area ecoregions exhibited different patterns in fire frequency (Pantanal > Humid Chaco > Dry Chaco) (Fig. SM1). Fires were most frequent in the Pantanal, occurring more than five times during the 2001–2020 period, followed by the Humid Chaco (3 to 4 fire occurrences) and the Dry Chaco (1 to 2 occurrences), indicating a lower occurrence than in the other ecoregions. No clear trend in fire intensity was observed throughout the time series (Fig. 5). Spatial analysis revealed that fire intensity was highest (1.3294×10^{7} kW) in the Dry Chaco in 2010. On average, fire intensity in the Humid Chaco can be considered low, while in the Dry Chaco and the Pantanal fire intensity ranged from moderate to high.

3.2. Predictive models

Among the three models tested, Random Forest (RF) yielded the highest precision (87 %), with a Kappa concordance index of 0.74 (Fig. 6). The best performing general additive model (GAM) yielded a precision of 73 % and a Kappa concordance index of 0.43, while the best performing generalized linear model (GLM) yielded values of 70 % and 0.39, respectively. Based on variable importance, the RF model identified maximum temperature, tree cover and livestock as the most important variables affecting fire occurrence in the Chaco Region (Fig. 3-a).

While the RF model provided the best predictive performance, the relationship between individual predictor variables and the probability of fire occurrence is difficult to interpret. By contrast, although the GLM and GAM models performed less well than the RF model, they provided useful information on the relationship between predictor variables and fire activity (Fig. 6). The GLM model revealed positive correlations between temperature and fire occurrence and negative correlations between precipitation and Vapour Pressure Deficit (VPD) (Table 3-b). VPD was generally higher in the dry Chaco and lower in the Humid Chaco. Additionally, analysis of topographic variables showed that lower altitude above sea level increased fire probability. High net primary productivity (NPP) was positively correlated with fire occurrence. The percentage of tree cover was negatively correlated with fire probability,

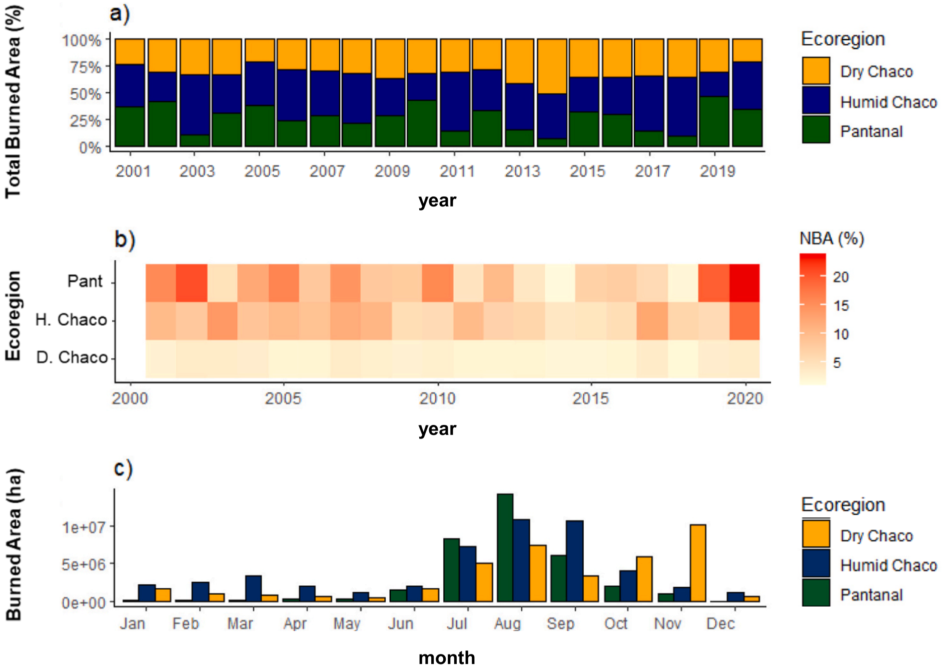

Fig. 3. Burning area patterns in the three ecoregions for the study period (2001–2020): a) stacked bar chart representing the individual percentage (0–100 %) of the burned area attributed to each ecoregion (Dry Chaco, Humid Chaco and Pantanal); b) Average Normalized Burned Area (NBA) per year and c) distribution of accumulated burned area per month.

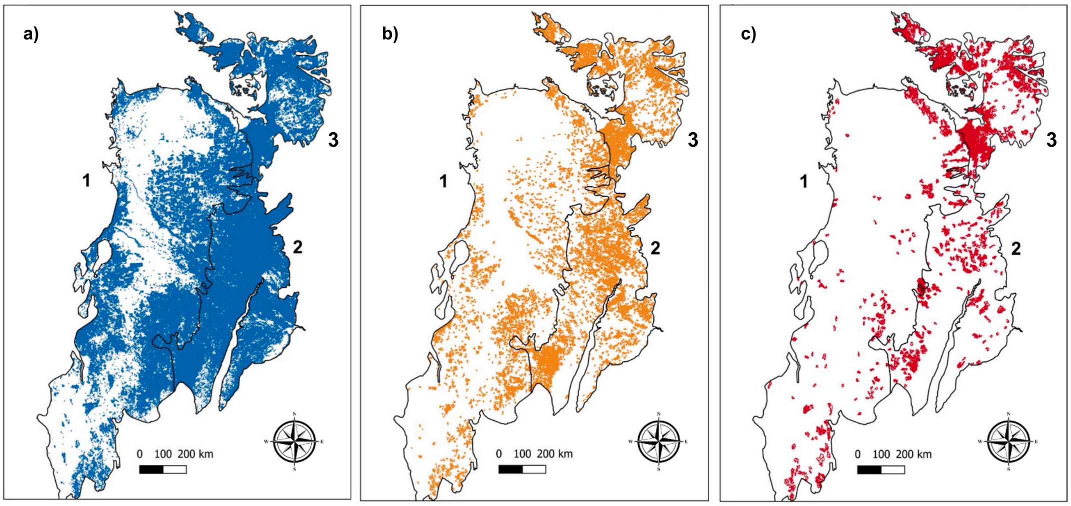

Fig. 4. Spatial distribution of fire scar size class over the 2001–2020 period in the three ecoregions: a) Small: < 1000 ha; b) Medium: 1000–5000 ha; c) Large: > 5000 ha. Ecoregions are labelled as follows: 1-Dry Chaco; 2-Humid Chaco; and 3-Pantanal.

while land use variables related to savannas and grasslands were positively correlated. Livestock was also positively correlated with fire occurrence. The GAM model yielded similar results but with higher prediction probabilities than the GLM. Unlike GLM, which uses simple coefficients, the GAM model uses smoothed functions to capture complex, non-linear relationships between the predictor variables and fire occurrence, providing more nuanced predictions (Table 3c).

Results of the three modelling approaches were consistent in depicting the spatial pattern of fire occurrence, indicating a decrease in fire probability from east to west. This indicates that fire occurrence was most pronounced in the Humid Chaco and the Pantanal.

4. Discussion

4.1. Characterizing fire patterns

Our study provides a comprehensive analysis of fire patterns over a 20-year period in the Gran Chaco and Pantanal regions, providing valuable insights into the spatial and temporal distribution of fire events. This characterization is crucial for understanding the dynamics of fire in these biodiverse and ecologically sensitive areas.

The prevalence of burning activity in the last two decades highlights the ubiquitous nature of fire as an important disturbance process shaping environmental conditions across the three ecoregions. Fire occurrence was most pronounced in all regions during the dry season,

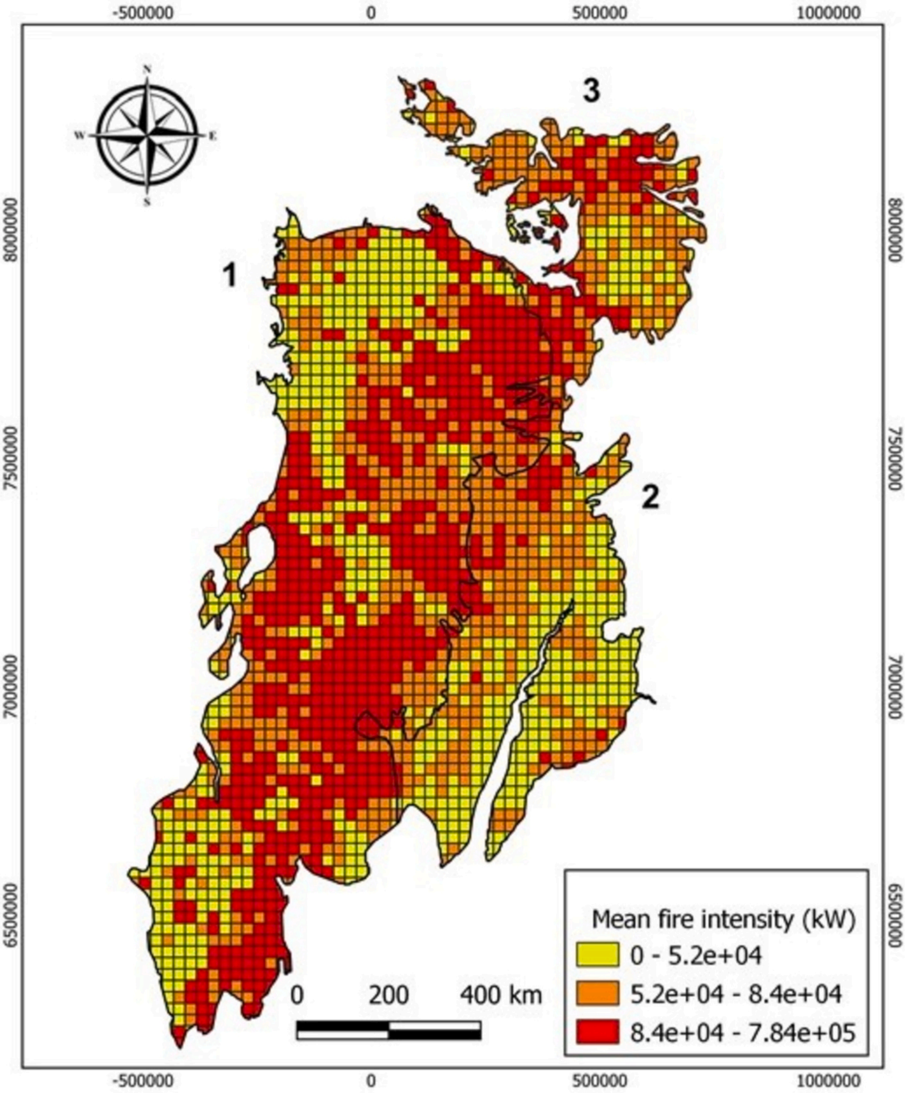

Fig. 5. Mean annual fire intensity (Kilowatts) across the three ecoregions during the last two decades. Ecoregions are divided into cells with a size of 6.25 km^2 and labelled as follows: 1-Dry Chaco; 2-Humid Chaco; and 3-Pantanal.

when the growth of fuels following the wet season provides abundant, connected and dry fuels. Notably, in 2020, when the highest total burned area of the decade was recorded -with almost 12 million hectares burnt- the precipitation decreased from 1433 mm to 940 mm. This reduction probably increased ignition rates and fire spread, as observed in studies attributing large fires in 2020 to extreme drought and high temperature (Garcia and de Oliveira Roque, 2021; Mataveli et al., 2021; Marengo et al., 2021; Libonati et al., 2022). The extreme drought in 2020 greatly exacerbated fire activity, affecting almost one-third of the Pantanal region, with over 40,000 km^2 of natural vegetation and agricultural land burned and with severe repercussions on biodiversity (Libonati et al., 2022; Kumar et al., 2022). Additionally, the smoke from these fires contributed to increasing greenhouse gas emissions and coincided with the COVID-19 pandemic, posing an additional risk to public health by potentially exacerbating respiratory problems and interacting negatively with the ongoing epidemic (Oliveira et al., 2020).

Fire frequency was higher and fire intensity lower in the Humid Chaco and Pantanal than in the Dry Chaco, where fires were less frequent but more intense, in a pattern that is probably related, to fuel type and condition (San Martin et al., 2023). Fire intensity and behaviour are strongly influenced by several factors: land use, fuel abundance, type and condition, weather and ignition sources (Flannigan et al., 2013). While fire frequency is higher in the Humid Chaco and Pantanal, fire intensity is comparatively lower in these ecoregions, for the following possible reasons: 1) the areas are dominated by savanna-type vegetation supporting frequent, low-severity fires and 2) higher fire occurrence reinforces the presence of more continuous, fine fuels that support low-intensity surface fires. The significant gradient in average annual precipitation (Fig. SM2), decreasing from east to west, favours water availability in Pantanal and Humid Chaco, which strongly influences the fuel type and condition. This increased rainfall regime results in eastern landscapes in the Humid Chaco and Pantanal being dominated by flooded pastures and small forest patches in small islands with an abundance of burnable fine fuel. The high rainfall regime in both ecoregions leads to high biomass accumulation, which under extreme summer temperatures (Fig. SM3) provides abundant, well-connected dry fuels that can facilitate fire spread. The increase in fire incidence during the dry season in the Humid Chaco and the Pantanal may therefore be mainly related to high biomass productivity, seasonal fuel drying and an increasing number of ignitions of anthropogenic origin (Archibald et al., 2013; San Martin et al., 2023).

By contrast, the less productive and connected fuels associated with the mosaic of woody and non-woody vegetation in the Dry Chaco results in infrequent, small fires. Here, a more heterogenous mosaic of forest,

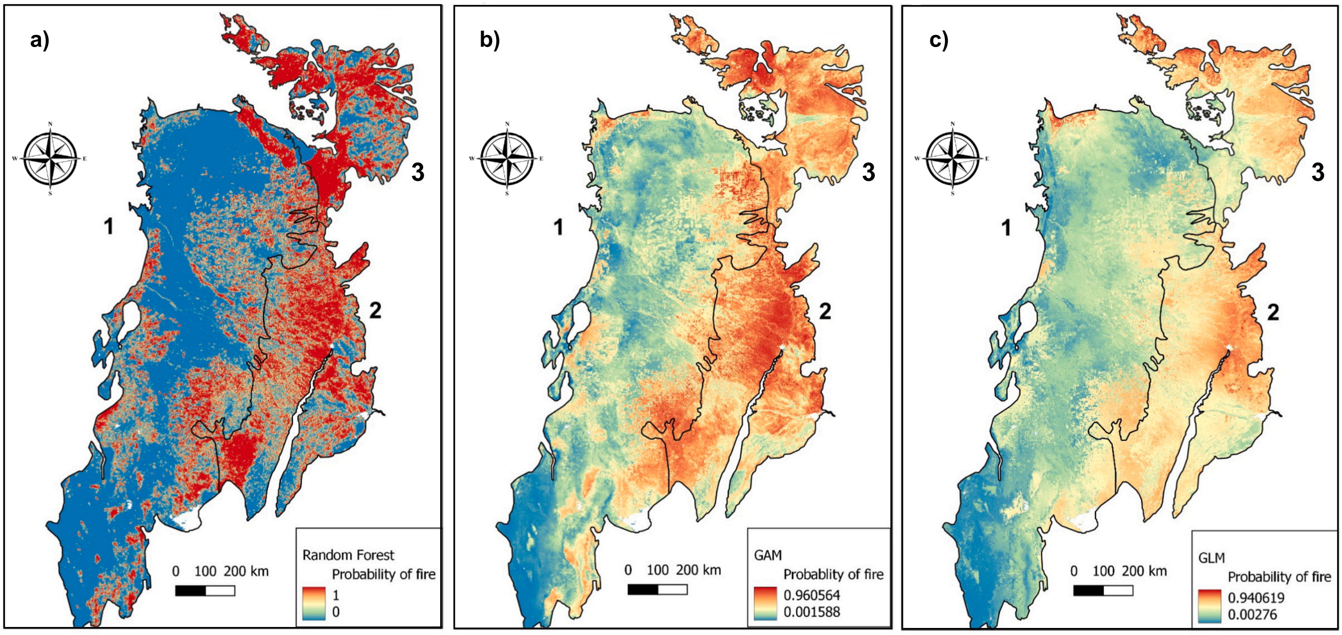

Fig. 6. Spatial distribution of the probability of fire occurrence derived from: a) Random Forest, b) GAM and c) GLM models. Values range from 0 to 1 (low to high probability of fire occurrence). Ecoregions are labelled in black as follows: 1-Dry Chaco; 2-Humid Chaco; and 3-Pantanal.

Table 3
Model results: a) Variable importance rankings for the RF model, based on Mean Decrease Accuracy and Mean Decrease Gini. Higher values for these indices indicate greater importance of the variable in predicting the outcome. b) Summary of the GLM model. c) GAM model fit statistics, including Estimated Degree of Freedom (EDF), Degree of Freedom (DF), Chi-Square, and *p*-value for continuous variables.

Model	Variable	Mean Decrease Accuracy	Mean Decrease Gini		
a) RF	DEM	112.63	82,986.93		
	VPD	117.71	60,584.17		
	Tree cover	201.20	67,569.14		
	Precipitation	104.84	68,108.49		
	Cattle	177.93	115,101.70		
	NPP	140.67	70,702.72		
	Tmax.	210.06	96,127.98		
b) GLM	Variable	Estimate	Std. Error	Z Value	Pr(>|z|)
	Intercept	-2.583e+00	1.313e-01	−19.673	<2e-16***
	DEM	−8.795e-04	1.355e-05	−64.908	<2e-16***
	VPD	−3.294e-01	1.081e-02	−30.481	<2e-16***
	Tree Cover	−2.867e-02	2.742e-04	−104.541	<2e−16***
	Precipitation	-1.553e-02	1.094e-04	−141.912	<2e-16***
	Cattle	2.614e-05	1.750e-06	14.931	<2e-16***
	NPP	8.269e-03	7.468e-05	110.729	<2e-16***
	Tmax	1.599e-01	1.387e-03	115.305	<2e-16***
c) GAM	Variable	EDF	DF	Chi Square	p-value
	DEM	8.832	8.98	5573	<2e-16***
	VPD	8.942	8.99	2695	<2e-16***
	Tree cover	8.5	8.93	5331	<2e-16***
	Precipitation	8.89	8.99	3424	<2e-16***
	Cattle	8.95	8.99	5191	<2e-16***
	NPP	8.93	8.99	2260	<2e-16***
	Tmax.	8.98	9.00	8349	<2e-16***

scrublands, grasslands and savanna vegetation probably hinders fire spread but supports higher fire intensity when fires occur. This may result from woody vegetation accumulating under a regime of infrequent fires, which burn intensely in the presence of fire.

The irregular distribution of fire size across the Gran Chaco and Pantanal, with the predominant occurrence of small fires (<1000 ha), is a characteristic pattern of human transformed landscapes, where deforestation and agriculture are prevalent (Archibald et al., 2013). On the other hand, larger fires were primarily concentrated in areas within the northeast region that are less impacted by grazing and agriculture, occupying a significant portion of the Pantanal ecoregion. These large fires may be the result from the interplay of an extended dry season and the presence of vast areas of well-connected fine fuels that dry seasonally (Marques et al., 2021; Bernardino et al., 2021). However, human activities amplify environmental factors that control the presence of fire. In the Pantanal, most fires are of anthropogenic origin; only 5 % are attributed to natural causes (Menezes et al., 2022) and human activities are carried out in a large part of the burned area (84 %). Here, rangeland managers intentionally burn large areas of the Pantanal each year to improve range condition and forage availability. This intentional burning to expand rangelands for livestock farming and agriculture has a strong impact on patterns of fire activity, leading to an increase in fire frequency while decreasing fire intensity.

In the Pantanal, land use changes, infrastructure development and regional policies serve as fire precursors (Baumann et al., 2016; Leal Filho et al., 2021; Magalhães and Evangelista, 2022).

New infrastructure projects, such as roads, highways and urban expansion, are constructed in previously undeveloped areas, thus fragmenting natural habitats and introducing new ignition sources and increasing the likelihood of human-caused ignitions. Indeed, Magalhães and Evangelista (2022) suggested that the proximity of river and roads to wildland areas in the Pantanal were responsible for the worst fire episode recorded in its history. In the 2020 fire season, they found that most fire sources (60 %) were identified as being within 5 km of human infrastructures including roads, waterways, and railways.

In the Chaco ecoregions, the spatial distribution of fire is also related to human presence driven primarily by land use modification and fuel composition. In terms of structure and composition, the Humid Chaco shows some similarities with the Pantanal, where the vegetation also consists of grasslands, savannas and flooded woodlands, and fine fuels (grasses) are abundant and well-connected. Furthermore, livestock is more abundant in the Humid Chaco (1.1/km^2) and in the Pantanal (0.85/km^2), further promoting the predominance of grasses. Conversely, in the Dry Chaco fewer cattle (0.3/km^2) and associated anthropogenic ignitions are combined sparse and less connected vegetation, limiting fire occurrence and spread (Zeballos et al., 2023). Restrictions on deforestation within the region have motivated the purchase of large areas of land in the Paraguayan Chaco, where clearing for grazing and agricultural activities are allowed (Milán and González, 2022). This situation led to increased use of fire for land clearing, cleaning, and grass renewal for cattle rearing. Therefore, regional policies may indirectly exert a strong influence on the shift in fire regimes.

4.2. Model results and predictions

The main results of all tested models (RF, GLM, GAM) reveal a consistent pattern of increasing fire occurrence across an east to west environmental gradient from the wetter Pantanal and Humid Chaco to drier Dry Chaco. Previous research has already highlighted the essential role of environmental factors in controlling fire distribution in subtropical ecosystems (Bravo et al., 2010, 2014; Roman-Cuesta et al., 2014). Grasslands and savanna systems often experience frequent fires and large burned areas after periods of fine fuel growth (increased precipitation) followed by fuel desiccation (drought) (Arganaraz et al., 2015).

Among the climatic factors influencing fire occurrence in the Gran Chaco and Pantanal regions, temperature, precipitation and vapour pressure deficit (VPD) are key variables. The Dry Chaco is characterized by higher temperatures and VPD, coupled with lower precipitation and is also the region with the lowest fire occurrence. On the other hand, the Humid Chaco and Pantanal are characterized by higher humidity. Unlike other regions where climatic factors may predominantly drive fire activity (Bradstock, 2010; Abatzoglou and Williams, 2016; Pausas and Ribeiro, 2013), the synergy with other factors, such as fuel availability and land use practices, better explains fire incidence in these ecoregions.

Therefore, climate variables alone cannot fully account for fire occurrence, as the presence of livestock and the percentage of tree cover have a notable influence on the outcome of the different models. In the GLM model, fire occurrence was positively related with the presence of cattle. During the last decades, the high global demand for meat has promoted land use changes and increasing deforestation rates in these ecoregions (Canova et al., 2021). Livestock farmers, in turn, often use fire for pasture renewal and land clearing (Kunst, 2011). Regarding tree cover, our findings indicated an inverse relationship, with increased fire occurrence corresponding with diminished tree cover. This can probably be attributed to the increase abundance of fine herbaceous fuels in less forested areas, fine fuels that promote fire spread. In these ecoregions, several ecological studies have explored the flammability of native trees (Jaureguiberry et al., 2011; Santacruz-García et al., 2019). Although it is generally considered that dominant Chaco vegetation exhibits high to very high flammability, it is also important to note that many of the previous studies only focused on the Argentine Chaco region. As a result, the role that non-native trees play in mediating fire activity and intensity is still poorly understood and deserves to be addressed in greater detail in future studies.

Previous studies have highlighted the predominance of fire ignitions of anthropogenic origin (∼90 %) in these ecoregions (Menezes et al., 2022). These human-driven ignition sources emphasize the need for future studies that address variables like land tenure, coordination of agricultural burning and burning calendars, and governance regarding burning regulation. The primary variable associated with human presence in our study was cattle. Cattle can have both positive and negative influences on fire occurrence in neotropical ecosystems. Positive feedback may arise when livestock graze on vegetation, thereby reducing fuel load and lowering the risk of large-scale wildfires (Bernardi et al., 2019). Conversely, there may be negative feedback when cattle managers contribute to human-caused ignitions by engaging in activities such as burning grasslands to clear vegetation (Pivello et al., 2021) thus preventing the regrowth of closed forests. This practice is common in these ecoregions, and when applied improperly and combined with climatic conditions, changes in land use can result in increased occurrence and intensity of wildfires. While our results indicated a positive correlation between fire occurrence and the presence of cattle, the relationship between human activity and fire needs further examination.

4.3. Uncertainties and limitations

Despite the comprehensive approach adopted in this study to analyze fire regimes and their drivers, some uncertainties and limitations remain. First, remote sensing data such as MODIS and the Global Fire Atlas, while providing extensive temporal and spatial coverage, also have some limitations in spatial resolution and underestimate both the frequency and extent of small and low-intensity fires (Giglio et al., 2006; Roy et al., 2008). MODIS sensor may miss up to 24–37 % of smaller fires and their associated burned area (Randerson et al., 2012; van der Werf et al., 2017) which is of particular importance in regions with frequent small-scale fires. Additionally, cloud cover and atmospheric conditions can obscure satellite observations, potentially affecting the accuracy of fire detection and estimation of the burned area (Roy et al., 2008). On the other hand, the temporal resolution used here may not have captured specific events that play important role in regional weather such as the South American low-level jet, upper-level jet stream, warm and cold fronts and the subtropical jet stream. These factors may influence fire occurrence and should be further studied using a more refined temporal scale.

Second, the study period (2001–2020) may not fully capture long-term trends and variability in fire activity, particularly in the context of climate change and evolving land use practices. The relatively short time frame may limit the ability to discern broader patterns and drivers of fire dynamics that operate on decadal scales. Future prospects should include extending the study period to encompass a longer time frame, which would provide more comprehensive insights into fire ecology trends and enhance the accuracy of conclusions about fire dynamics in these ecoregions.

Third, even though all models used in the study (RF, GLM, GAM) produced a good response, they also have some inherent limitations.

While Random Forest provided the best predictive performance, it is a black-box model making it difficult to interpret the relationships between predictor variables and fire occurrence. Conversely, GLM and GAM, though more interpretable, showed lower predictive accuracy. In the present study predictor variables were selected on the basis of a comprehensive literature review and expert criteria. Notwithstanding, models will probably benefit from the inclusion of socioeconomic variables, which are useful for relating wildfire risk and social vulnerability (Chas-Amil et al., 2022). Unfortunately, this type of data is not available or is difficult to access for the region.

Finally, as in most of the studies that consider climatic variables, there is some degree of uncertainty associated with the climatic and environmental data used as inputs for the models. Climate variables may yield different results depending on specific variables related to temperature and precipitation. Additionally, livestock data is very coarse and may not accurately reflect the current land use situation, leading to potential misinterpretations in model outputs.

4.4. Implications for management

The findings of this study have important implications for fire management in the Gran Chaco and Pantanal regions. Understanding the spatiotemporal patterns of fire occurrence and intensity and their relationship with climatic, environmental and anthropogenic drivers can provide relevant information for developing more effective fire management strategies.

At local scale and for landowners, the study findings highlight the importance of integrating climate change projections into fire management planning. With a potential increase in fire activity and extreme fire events under changing climatic conditions, managers need to develop adaptive strategies including enhancing firebreaks, implementing controlled burns under safer conditions during the appropriate season (Martins et al., 2022) or fostering land restoration using fire-resistant species adapted to local conditions. It is also important to implement preventive measurements to protect fire-sensitive moist forest such as gallery and riparian forests (Lapola et al., 2023) or sensitive species such as *Alchornea castaneifolia*, *Bactris glaucescens* and *Genipa americana* (Pott, 2020; Damasceno-Junior et al., 2021).

Forest degradation and changes in fuel composition to more homogeneous, continuous and highly susceptible to ignition landscapes also play a crucial role across these ecoregions. In the past two decades, there has been a significant increase in Eucalyptus plantations in Paraguay, Argentina, and Brazil, driven by the demand for pulp production (Grossman, 2015; Denegri et al., 2021; Florêncio et al., 2022). As observed elsewhere, the conversion of sparse, heterogeneous native vegetation to highly flammable, continuous and homogeneous eucalypt plantations, known for their highly susceptibility to ignition, can promote fire spread (Paritsis et al., 2018; McWethy et al., 2018). Additionally, the introduction of non-native grasses and shrubs in livestock and agricultural production increases the combustible biomass, diminishes tree cover, and promotes fire spread, resulting in a more frequent occurrence of large fires (Silvério et al., 2013; Maillard et al., 2020).

This study demonstrated that most fires occurred in the Humid Chaco and Pantanal ecoregions, which comprise a greater proportion of the land transformed by human activity, especially for livestock farming.

The significant role of anthropogenic factors in driving fire activity suggests that management efforts should also focus on regulating land use practices and the need for targeted fire adaptive management strategies and climate change. However, responses should be designed according to the specific needs of each country. Argentina and Paraguay face similar challenges, mainly related to deforestation for agricultural and livestock expansion. Although sustainable forest management and reforestation programs exist in Argentina, they are limited by resource shortages and fragmented policies (De Marzo et al., 2022). Similarly, the enforcement of environmental laws is limited in Paraguay, where fire prevention programs require greater investment in infrastructure, funding and community participation (Coronel et al., 2021). In both cases, encouraging community involvement in fire prevention programmes, strengthening collaboration between government agencies and local communities and improving enforcement of environmental laws through adequate resources and training for local authorities are essential.

Bolivia faces similar challenges with land burning mainly due to agricultural expansion. Here, the “Law of Mother Earth” aims for sustainable management but struggles with enforcement due to lack of infrastructure and funding (Romero-Muñoz et al., 2019). Effective enforcement of environmental laws, investment in infrastructure and integrating traditional land-use practices with modern fire prevention strategies could help mitigate fire risks. Finally, the Pantanal has experienced devastating fires exacerbated by agricultural expansion and extreme climatic conditions in Brazil. Despite efforts like the Program for Prevention and Combating Fires in the Pantanal, coordination among local actors remains challenging (Libonati et al., 2022; Marengo et al., 2021). Improving coordination between federal, state and local authorities in fire prevention and integrating fire monitoring systems with land use planning are crucial. Although specifically indicated for the Brazilian case, there is a need for coordinated fire management across the Gran Chaco and Pantanal regions. Transboundary cooperation and sharing sustainable practices, data and resources could enhance the effectiveness of fire management strategies. Establishing regional fire management plans that account for the unique ecological and socioeconomic contexts of each ecoregion could help mitigate the impacts of fire and preserve the ecological integrity of these highly diverse ecoregions.

5. Conclusions

Our study is the first spatiotemporal analysis of fire patterns in the Gran Chaco and Pantanal ecoregions. The findings highlight the influence of temperature, aridity, vegetation type and land use on driving fire activity and intensity within these ecoregions. The main findings suggest that conditions within the Humid Chaco and Pantanal ecoregions foster frequent large and less intense fires, whereas less frequent but more intense fires are favoured in the Dry Chaco ecoregion. Recurrent fires in the Humid Chaco and Pantanal are mainly of anthropogenic origin and are sustained by the abundance of fine fuels that in turn support recurrent and low-intensity fires. Higher temperatures, longer dry seasons and an increasing number of ignition sources (given by land use transformation), could amplify the prevalence of fire activity in the future, given the strong seasonality that promotes fuel drying and fire spread.

Our findings indicate that fire occurrence has remained relatively constant over the last two decades, with recurrence mainly depending on climatic and anthropic variables. Although an increase in fire occurrence was not observed, it is essential to focus on current management practices and environmental conditions that may influence future fire activity. Such practices include continued application of intentional burning to manage pastures, lack of management controls for intentional burning, and projected variation in precipitation and temperatures. Considering the positive correlation between fire occurrence and the presence of cattle, further studies should carry out detailed exploration of the relationship between human activity and fire, or the role of non-native grasses introduced for livestock production.

Predictive models are useful for understanding the distribution of historical fire events and exploring the variables responsible for its occurrence. These may be valuable tools that should be taken into consideration in the development of fire prevention and management systems. Unravelling the components of the fire regime and understanding their relationship with climate and anthropogenic variables are essential for developing effective fire management strategies in these fire-prone ecoregions. By using GLM, GAM and Random Forest models, we also contribute to the growing body of literature on fire ecology by demonstrating the strengths and limitations of different statistical approaches in predicting fire occurrence. Our findings highlight the importance of using a combination of models to enhance the reliability and robustness of fire predictions and as valuable tools to develop fire prevention and fire management systems.

CRediT authorship contribution statement

Cristina Vidal-Riveros: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bryce Currey:** Visualization, Validation, Supervision, Software, Methodology, Formal analysis, Data curation. **David B. McWethy:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Conceptualization. **Marie Ange Ngo Bieng:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Pablo Souza-Alonso:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.176823.

Data availability

Data will be made available on request.

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