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Title: Fire threats to protected areas in the Amazon–Cerrado transition zone

Short Running Title: Fire threats to Amazon–Cerrado PAs

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Author Contributions:

EVB and LOA conceived the study and established the research design, including the definition of the 25 federal and state Protected Areas (PAs) analyzed across the Amazon, Cerrado, and transition biomes; PHAL developed the BRASA integrated burned area product, performing the multi-sensor fusion of MCD64A1, Fire_CCI, and MapBiomas Fire datasets, and provided the technical data architecture and fire metrics at 30-m spatial resolution; EVB, CHLSJ, ALRF, PRMP, JCV, WML, BVS, ASS, AMP, AQSN, NSF, HGPF, ICC, CMS, WAS, and TCSR performed geospatial data curation and reprojection to the SIRGAS 2000 reference system for the 25 PAs; EVB, CHLSJ, ALRF, and PHAL conducted the spatial intercomparison analysis between BRASA and GABAM, quantifying the systematic underestimation of burned area by global datasets; EVB, MBA, and DPS performed the non-parametric statistical modeling, including the Wilcoxon signed-rank test for product intercomparison, Mann–Whitney U tests for comparisons between Strict Protection and Sustainable Use categories and between federal and state jurisdictions, and Kruskal–Wallis H tests for comparisons across specific PA typologies (EPAs, ERs, BRs, PNHRs, and Parks); EVB, DPS, and LOA analyzed the Spearman rank correlations between annual burned areas and the Oceanic Niño Index (ONI), identifying the Gurupi Biological Reserve as the only PA with significant ENSO-related fire sensitivity ($\rho = 0.58$; $p = 0.007$); EVB, CHLSJ, DPS, TCSR, and LOA led the ecological interpretation of fire regimes across land use and land cover (LULC) classes, identifying the predominance of fire in Savanna Formations (78.9% in the Cerrado during the 2010 peak) and Forest Formations (68.1% in the Amazon during the 2016 peak), as well as the association with Pasture and Mosaic of Uses classes in the transition zone; EVB, CHLSJ, DPS, TCSR, and LOA wrote the original draft; all authors contributed to the critical review of the intellectual content and approved the final version for publicatio

FIRE THREATS TO PROTECTED AREAS IN THE AMAZON–CERRADO TRANSITION ZONE

ABSTRACT

The transition zone between the Amazon and Cerrado biomes represents a strategic ecotone where fire plays contrasting ecological roles. In Brazil, a large portion of this ecotonal region occurs in the state of Maranhão. This study analyzed spatio-temporal fire dynamics from 2001 to 2020 across 25 federal and state Protected Areas (PAs) to evaluate the effectiveness of legal protection against fire disturbances. Using the BRASA product, a multi-sensor fusion of MCD64A1, Fire_CCI, and MapBiomas Fire, fire regimes were characterized through burned area, recurrence, seasonality, and land-use associations at 30-m resolution. Critical fire peaks occurred in 2004 to 2005, 2010, and 2015 to 2017. In the Amazon, the Gurupi Biological Reserve experienced the highest annual impact, 42.3% BA in 2016, with significant correlation to ENSO events ($\rho = 0.58$; $p = 0.007$). In the Cerrado, the Nascentes do Rio Parnaíba National Park accumulated over 1.8 million ha burned, with a high recurrence of 4 to 11 events. Statistical analyses revealed that the management category significantly influenced the burned area only in the Cerrado ($p = 0.036$), whereas administrative jurisdiction did not. Fire primarily affected the Savanna Formations in the Cerrado and the Forest Formations in the Amazon. These results indicate that while sensitive units respond to climatic variability, fire dynamics are largely driven by local anthropogenic pressures regardless of the legal framework. This study demonstrates the critical role of integrated spatial monitoring for effective fire governance in complex ecotonal landscapes.

Keywords: Remote Sensing, Burned area, Landscape transformation, Ecological transition zone

INTRODUCTION

The state of Maranhão occupies a unique position within the Brazilian territory, constituting an extensive and complex ecological transition zone between the Amazon and Cerrado biomes, which account for approximately 35% and 65% of its total area, respectively (IBGE 2024). This biogeographical configuration results in a landscape characterized by high biodiversity and environmental heterogeneity. However, it also renders the region particularly vulnerable to anthropogenic pressures, such as the expansion of the agricultural frontier and shifts in natural disturbance regimes (Marengo et al. 2022; Guo et al. 2023). Within this context, understanding the dynamics of disturbances such as fire in this ecotone is crucial, given the potentially distinct and not fully understood responses of these transition systems.

While in the Amazon biome fire is fundamentally an anthropogenic disturbance, alien to the natural functioning of forest ecosystems and a vector of degradation and biodiversity loss (Bush et al. 2008; Aragão et al. 2018), in the Cerrado biome it is an intrinsic evolutionary component (Rosan et al. 2022). In this context, it is essential to distinguish between "good fire" and "bad fire." In fire-adapted savannas such as the Cerrado, low-intensity, early dry-season burns with longer return intervals may play a regulatory ecological role: they reduce accumulated fuel loads, stimulate resprouting, synchronize flowering in some herbaceous species, and help maintain open physiognomies and biodiversity (Fontenele and Miranda 2024). Conversely, high-intensity, late dry-season fires, recurrent in short intervals and frequently associated with anthropogenic ignition sources, tend to exceed the adaptive thresholds of native species (Nieman et al. 2022). These "bad fires" can damage seed banks, increase tree mortality, favour invasive grasses, simplify vegetation structure, and intensify soil nutrient losses (Balch et al. 2024).

In this context of increasing socio-environmental challenges, Protected Areas (PAs) are consolidating as central institutional instruments for biodiversity protection. In Brazil, these areas are regulated by the National System of Protected Areas (SNUC – Law No. 9,985/2000), which divides them into two major groups with distinct management types: Strict Protection (SP) units, aimed at strict preservation and indirect use of resources, such as National Parks and Biological Reserves; and Sustainable Use (SU) units, which allow human presence and regulated management, such as Environmental Protection Areas (EPAs), Extractive Reserves (ERs), and Private Natural Heritage Reserves (RPPNs). Although legally protected, PAs do not operate in isolation from the surrounding landscape and remain susceptible to external threats (Masullo et al. 2020). To mitigate such impacts, the SNUC establishes a buffer zone around most PAs, where human activities are subject to norms and restrictions regulated by the managing agency, aiming to minimize negative effects on the unit's interior (De Medeiros et al. 2021; Santos 2020).

Although macro-scale assessments (Geldmann et al. 2019) and regional studies (Rodrigues et al. 2022) have advanced the mapping of fire hotspots within Brazilian protected areas (PAs), a detailed understanding of the fire regime remains limited. The concept of a fire regime describes the recurring patterns of fire over time and space, typically characterized by metrics including frequency, intensity, size, seasonality, and severity Pivello 2011). In ecotonal regions, characterizing these patterns is essential to distinguish between natural ecological processes and human-induced disturbances (Eloy et al. 2019).. However, integrated research addressing metrics such as burned area, recurrence, and land-use associations within protected territories remains scarce, particularly in the critical Amazon–Cerrado transition of Maranhão (Silva-Junior et al. 2022; Da Silva Arruda et al. 2024). To overcome the inherent limitations of individual burned-area detection products (Pessôa et al. 2020), this study adopts an integrated approach based on the BRASA product (Leão et al. 2023), which combines multiple datasets to produce a more robust analysis of fire dynamics.

In light of the above, this study aims to evaluate the effectiveness of an integrated multi-sensor approach for monitoring fire dynamics in the Amazon-Cerrado ecotone. Specifically, the study seeks to: (i) assess the performance of the BRASA integrated product (Leão et al. 2023) in characterizing the spatio-temporal fire regime across state and federal PAs from 2001 to 2020; (ii) quantify burned area (BA) and fire recurrence within these units to identify critical peaks and vulnerability; and (iii) identify the main land use and land cover classes associated with BAs. By integrating these metrics, the study aims to contribute to understanding how anthropogenic pressures, especially those associated with agriculture, alter fire dynamics in areas designated for conservation, providing support for the effective management and protection of these units.

MATERIALS AND METHODS

Study Area

The state of Maranhão, with a total area of 329,651.478 km², is one of the largest Brazilian states in terms of area, occupying a strategic position in the Northeast region of the country (IBGE 2024). Thus, 25 federal and state PAs with mainland portions within the state limits were analyzed, totaling an area of 9,001,680.17 ha under legal protection (Figure 1). Of this total, 2,040,675.96 ha (22.7%) correspond to PAs in the SP group, while 6,961,004.21 ha (77.3%) belong to the SU group.

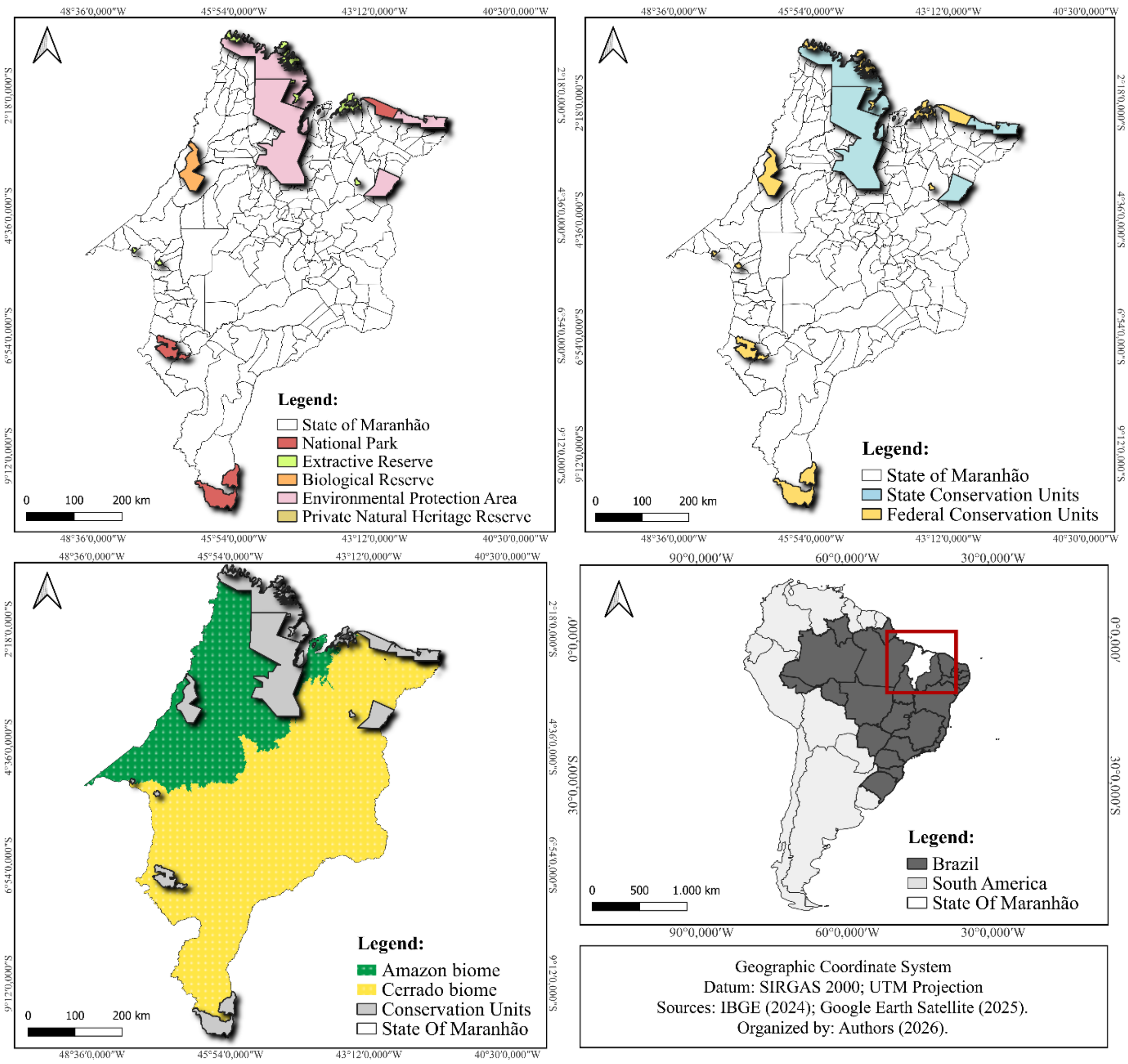

Fig 1: Location of Federal and State Protected Areas in Maranhão, Brazil

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The categorization presented in Table 1 (Supplementary Materials) follows the regulatory framework of the SNUC, which organizes protected territories into two functional clusters based on their restrictive levels. The

Strict Protection group, which encompasses NPs, BRs, and State Parks, is characterized by stringent preservation standards where biodiversity maintenance is prioritized by prohibiting the direct extraction of natural wealth. Conversely, the Sustainable Use group comprises EPAs, ERs, and PNHRs to integrate conservation with anthropized landscapes. Within this study's scope, these units range from vast EPAs with diverse land-use mosaics to ERs focused on the socio-ecological protection of traditional livelihoods and PNHRs that represent the contribution of private landholdings to the state's ecological stability.

Burned Area Data Integration

This study utilized the geospatial data generated by the MapFire Project, which provides a multitemporal analysis of environmental indicators through a historical series spanning up to 39 years for the state of Maranhão. Specifically, the research employed the BRASA product (Leão et al. 2023) to characterize spatiotemporal fire dynamics. This product enhances fire detection by fusing multiple burned area datasets, including MCD64A1 (V6.1), Fire_CCI (V5.1), and MapBiomas Fire (Collection 4), as illustrated in Figure 2 (Supplementary Materials). Such an integrated approach is designed to overcome limitations of individual products and improve accuracy in ecotonal regions (Moreno-Ruiz et al. 2023). The complete geospatial collection is publicly available through the MapFire platform (https://www.mapfire.info/) and the Zenodo repository (https://zenodo.org/records/18342645).

First, to ensure spatial and temporal compatibility between products, a pre-processing step was performed. Monthly data from MCD64A1 (500 m) and Fire_CCI (250 m) were reprojected to the SIRGAS 2000 reference system and resampled, using the nearest neighbor method, to a common spatial resolution of 30 m. This step was crucial for aligning the pixels of all datasets with the MapBiomas Fire spatial resolution (30 m), enabling pixel-by-pixel map algebra operations.

To establish a common historical series for all products, the analysis time interval was defined from 2001 to 2020. This period corresponds to the full historical series available for the Fire_CCI product, which has the shortest temporal coverage among the three integrated datasets. For each year within this range, the 12 reprocessed monthly mosaics from MCD64A1 and Fire_CCI were summed to generate annual binary mosaics (value 1 for pixels burned in any month, 0 otherwise). The MapBiomas Fire, already distributed as annual mosaics, was used directly

To perform the fusion, each annual binary mosaic was encoded with distinct values based on powers of two: MapBiomas Fire = 1, Fire_CCI = 3, and MCD64A1 = 7. Pixel-by-pixel overlay of these layers produced unique sums (e.g., 8 = 7+1), uniquely identifying which products detected fire at each location annually. The resulting annual sums generated the BRASA integrated raster, the main burned-area dataset for this research. From this 20-year time series (2001–2020), four fire regime metrics were derived at 30 m resolution within each PA: 1) first year of occurrence; 2) last year of occurrence; 3) fire frequency (total years with detected fire); and 4) fire recurrence, defined as the total number of annual fire observations per pixel across the time series. This annual integration standardizes the temporal unit of analysis, acknowledging that multiple detections may occur within a single year in monthly products.

Intercomparison between BRASA and GABAM

Before statistical analysis, an intercomparison was performed between BRASA and the Global Annual Burned Area Map (GABAM) to evaluate the consistency and potential improvements of the multi-sensor fusion product against an established independent dataset. GABAM was selected as a reference because it provides global burned area maps at 30-m resolution based on Landsat imagery (Long et al. 2019), enabling direct spatial comparison with BRASA. Both datasets were aligned to SIRGAS 2000 and clipped to the 25 PA boundaries to ensure spatial consistency.

In this context, the statistical significance of the differences between the two products was assessed using the Wilcoxon signed-rank test (Wilcoxon 1945). This specific test was chosen because fire data are non-parametric, typically exhibiting skewed distributions and a high frequency of zero values in years with low fire activity, which violates the assumptions of normality required for parametric tests (Ahad et al. 2014). The test statistic (W) is calculated according to Equation 1:

$$W = \sum_{i=1}^{n} [sgn(x_{1,i} - x_{2,i}) * R_i \quad (1)$$

In this equation, n is the number of paired observations or years, while $x_{1,i}$ and $x_{2,i}$ represent the annual burned area values for BRASA and MCD64A1, respectively. The term *sgn* denotes the sign function of the differences, which identifies which product recorded a higher value in a given year, and Ri represents the rank of the absolute differences. This statistical framework ensures that the identified gains in burned area detection are statistically significant and represent a consistent improvement over the standard global monitoring product across the historical series

Burned Area Statistics

Statistical analyses were conducted using non-parametric methods due to the characteristics of the analyzed response variables, specifically the accumulated total burned area (ATBA) and fire recurrence. These variables exhibited asymmetrical distributions, high dispersion, outliers, and heterogeneity of variances among the compared groups, as evidenced by exploratory graphical inspection (boxplots) and the lack of normality in the data.

Considering the wide variation in territorial extent among Protected Areas (PAs), analyses were performed using normalized metrics to minimize size-related bias and enable consistent comparisons across units. Consequently, the ATBA was expressed as a percentage of each PA's total area. This normalized metric reflects the relative burned area within each unit, representing the proportion of the protected territory affected by fire throughout the study period. The normalization was calculated according to Equation 2:

$$\text{Normalized burned area (\%)} = \left(\frac{Total\ burned\ area\ in\ the\ PA}{Total\ area\ of\ the\ PA}\right)x100 \quad (2)$$

Where Total Burned Area in the PA corresponds to the cumulative area detected by the BRASA product and Total Area of the PA is the official territorial extension of the unit.

Statistical comparisons were performed exclusively between PAs within the same biome or ecological context. Thus, Amazon PAs were compared only among themselves, and the same occurred for those located in the Cerrado and in the Amazon–Cerrado transition areas, which were analyzed separately. This strategy was adopted to reduce interpretative biases, given that these environments exhibit marked differences in vegetation structure, climatic conditions, natural fire regimes, and ecological processes, as evidenced by Geldmann et al. 2021. Consequently, the observed contrasts predominantly reflect the effects of management, anthropogenic pressure, or land use rather than intrinsic differences between distinct biomes.

From a statistical perspective, it is recognized that data stratification reduced the sample size in some groups, which may impact the power of inferential tests. Therefore, the sample size per group was previously evaluated, and statistical analyses were conducted only when minimum representativeness assumptions were met, including: (i) minimum sample size per group ($n \geq 5$); (ii) absence of extreme imbalance between compared categories; and (iii) stability of descriptive statistics (Cohen 2013; Conover 1999; Gotelli and Ellison 2004). When these criteria were not met, the analysis was restricted to descriptive statistics to avoid unstable inferences or low statistical power.

Consequently, for comparisons involving two independent groups, such as PAs in different management categories (Strict Protection vs Sustainable Use) and distinct administrative spheres (Federal vs State), the Mann–Whitney U test was used. This non-parametric method is appropriate for independent samples and non-normal distributions (Mann and Whitney 1947; Sirtori et al. 2019). The test statistic was calculated according to Equation 3:

$$U_1 = n_1 n_2 + \frac{n_1(n_1+1)}{2} - R_1;\ U_2 = n_1 n_2 + \frac{n_2(n_2+1)}{2} - R_1 \quad (3)$$

where R_1 and R_1 correspond to the sums of ranks for each group, with the test statistic being the smaller value between U_1 and U_2. For large samples ($n > 20$), the distribution of U approaches normality, allowing p-value calculation via z-approximation.

Data were organized into independent groups, considering the joint ordering of observations. Ties in values were handled by assigning average ranks, according to standard test procedures. For samples with sufficient size, p-values were obtained by normal approximation, while comparisons involving small samples were evaluated using the exact distribution. Analyses were conducted only when minimum sample representativeness assumptions were met.

For situations involving three or more independent groups, such as comparisons among specific PA categories (ER, BR, PNHR, EPA, and National and State Parks), the Kruskal–Wallis H test was used. This method is suitable for non-parametric data and independent samples (Kruskal and Wallis 1952). The test statistic was determined according to Equation 4:

$$H = \frac{12}{N(N+1)} \sum_{i=1}^{K} \frac{R_i^2}{i=1} - 3\,(N+1) \quad (4)$$

in which ni represents the sample size in group i and Ri the corresponding sum of ranks, with H being approximately distributed as chi-square with k-1 degrees of freedom.

Data were organized into independent groups through a joint ranking of observations, with ties handled by assigning average ranks. When the Kruskal-Wallis test indicated statistically significant global differences ($p<0.05$), post-hoc analyses were performed using Dunn's test with Bonferroni correction to control for Type I error. These analyses were implemented only when minimum sample representativeness assumptions were met. The entire computational workflow, ranging from geospatial data processing to statistical modeling, was developed in a Python environment (Van Rossum and Drake 2009). Specifically, the statistical tests were executed using the *kruskal* function from the SciPy library (Virtanen et al. 2020) and the scikit-posthocs package (Terpilowski 2019) for multiple comparisons.

Correlation between Burned Areas and Climatic Events (ENSO)

To investigate the relationship between the magnitude of burned areas within PAs and the occurrence of the El Niño–Southern Oscillation (ENSO) climatic phenomenon, a non-parametric statistical correlation analysis was employed. The Spearman's Rank Correlation Coefficient (ρ) was selected, as this technique is recommended for environmental variables characterized by asymmetric distributions and abrupt variations. As noted by Berenguer et al. 2021, time series of hotspots in tropical biomes frequently deviate from a normal distribution, rendering Spearman's correlation more suitable than traditional parametric tests, given that it operates on the ranking of observations rather than their absolute values.

The use of Spearman's rank correlation is further justified by its robustness in the presence of outliers, which, in the context of this study, represent extreme peaks in burned areas during severe droughts. This non-parametric measure assesses the strength and direction of the monotonic association between variables. Mathematically, the coefficient (ρ) is calculated according to Equation 5:

$$\rho = 1 - \frac{6\Sigma d_i^2}{n(n^2-1)} \quad (5)$$

This statistic captures monotonic trends, essential for identifying whether ocean temperature anomalies consistently correlate with fire occurrences in PAs (Silva et al. 2025). The coefficient ranges from −1 to +1, distinguishing inverse from direct associations. Using this approach, annual burned area was compared with the Oceanic Niño Index (ONI) at two levels: regional (sum of all PAs in Maranhão) and individual PAs. Hypothesis testing ($p<0.05$) assessed significance, identifying units with high climatic sensitivity where fire dynamics amplify with ocean-atmosphere anomalies (Pereira et al. 2021). Notably, climatic events act synergistically with anthropogenic pressures, significant correlation indicates climate creates fuel-drying conditions that facilitate human-induced ignitions in the transition region.

Integration with Land Use and Land Cover

To relate burned area dynamics to land use and land cover patterns, annual data from MapBiomas (Collection 10, 30 m spatial resolution) were integrated with the BRASA annual burned area product. Spatial analyses were performed using QGIS software (version 3.34.12). Considering that the source data were originally provided in the WGS 84 coordinate system (EPSG:4326), all layers were reprojected to the SIRGAS 2000 geographic reference system (EPSG:4674).

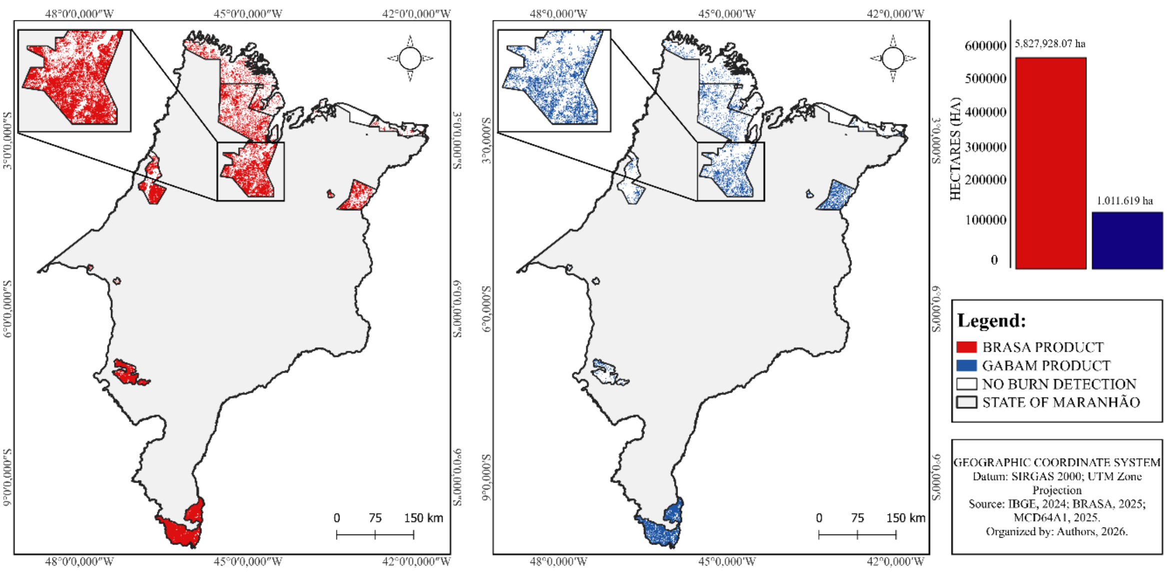
Using map algebra in QGIS, pixel-by-pixel cross-tabulation was performed between the BRASA burned area mask and MapBiomas land use/cover for each year (2001–2020), identifying the class associated with each burned pixel. Classes analyzed included natural vegetation (Forest Formation, Savanna Formation, Grassland Formation, Flooded Forest, Wet Grassland, Wetland, Mangrove) and anthropic types linked to recurrent fire use (Pasture, Mosaic of Uses, Temporary Crops), selected based on vegetation typology, biomass availability, and ecological fire responses (De Sousa et al. 2024; Pinto 2019).

RESULTS

Gain in Detection Sensitivity (BRASA vs. GABAM)

The comparison between the integrated BRASA product and the GABAM (Figure 3) dataset revealed substantial differences in burned area detection across the 25 Protected Areas in Maranhão. Considering the entire historical series from 2001 to 2020, BRASA detected a cumulative burned area of 5,827,928.07 ha, whereas GABAM mapped 1,011.619 ha within the same territories. This indicates that the multi-sensor fusion product identified approximately five times more burned area than the Landsat-based global dataset over the 20-year period.

Fig 3. Spatial intercomparison between BRASA and GABAM products in Maranhão PAs (2001–2020).



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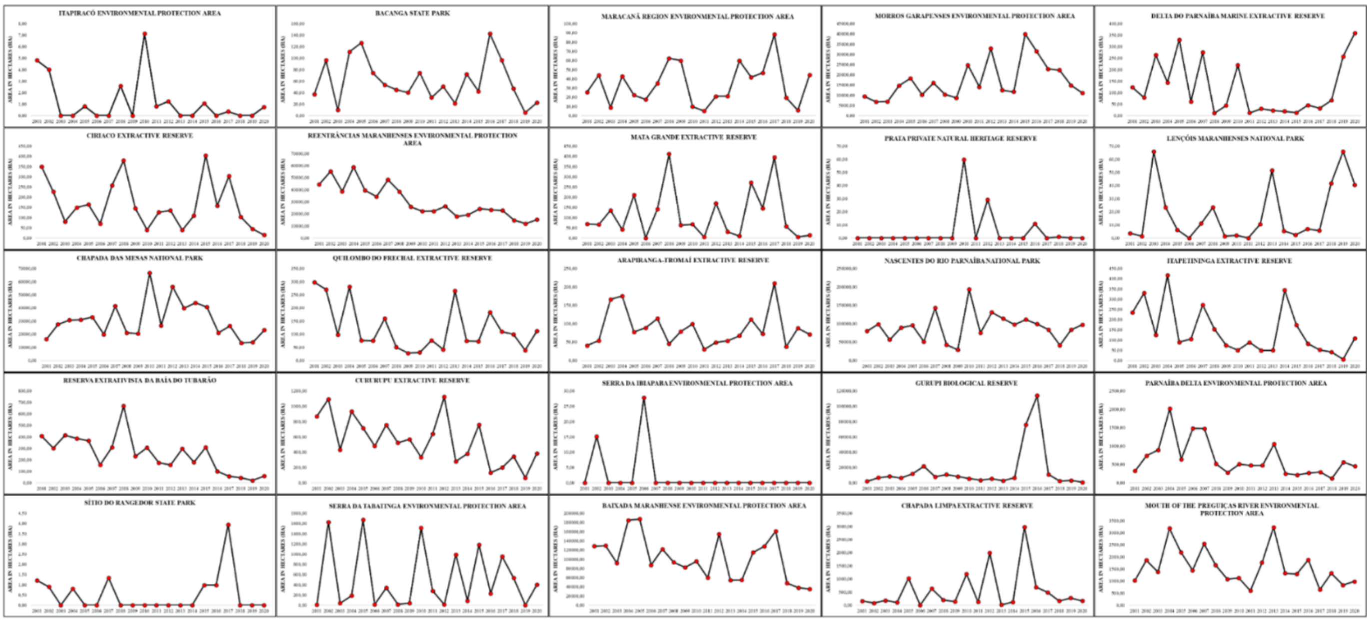
To statistically evaluate the differences between the two datasets, a Wilcoxon signed-rank test was applied to the 20 paired annual observations. The results showed that burned area estimates derived from BRASA were consistently higher than those obtained from GABAM across all years of the time series. The calculated test statistic was W = 210, corresponding to the maximum possible rank sum for n = 20, and the associated significance level was $p < 0.0001$. This result indicates a highly significant difference between the two datasets. Therefore, the larger burned area detected by BRASA cannot be attributed to random variability, but rather reflects a systematic improvement in fire detection capability relative to the reference global dataset throughout the historical series.

Spatio-Temporal Fire Dynamics and Critical Peaks

The analysis of fire dynamics across the 25 PAs of Maranhão between 2001 and 2020 allowed for the identification of temporal trends and variations in fire extent across biomes. Across the set of units, the years 2004, 2005, 2010, 2015, 2016, and 2017 stood out as the most critical, concentrating the highest peaks of BA (Figure 4).

Fig 4: Annual burned area (ha) in the Protected Areas of the state of Maranhão (2001 to 2020).



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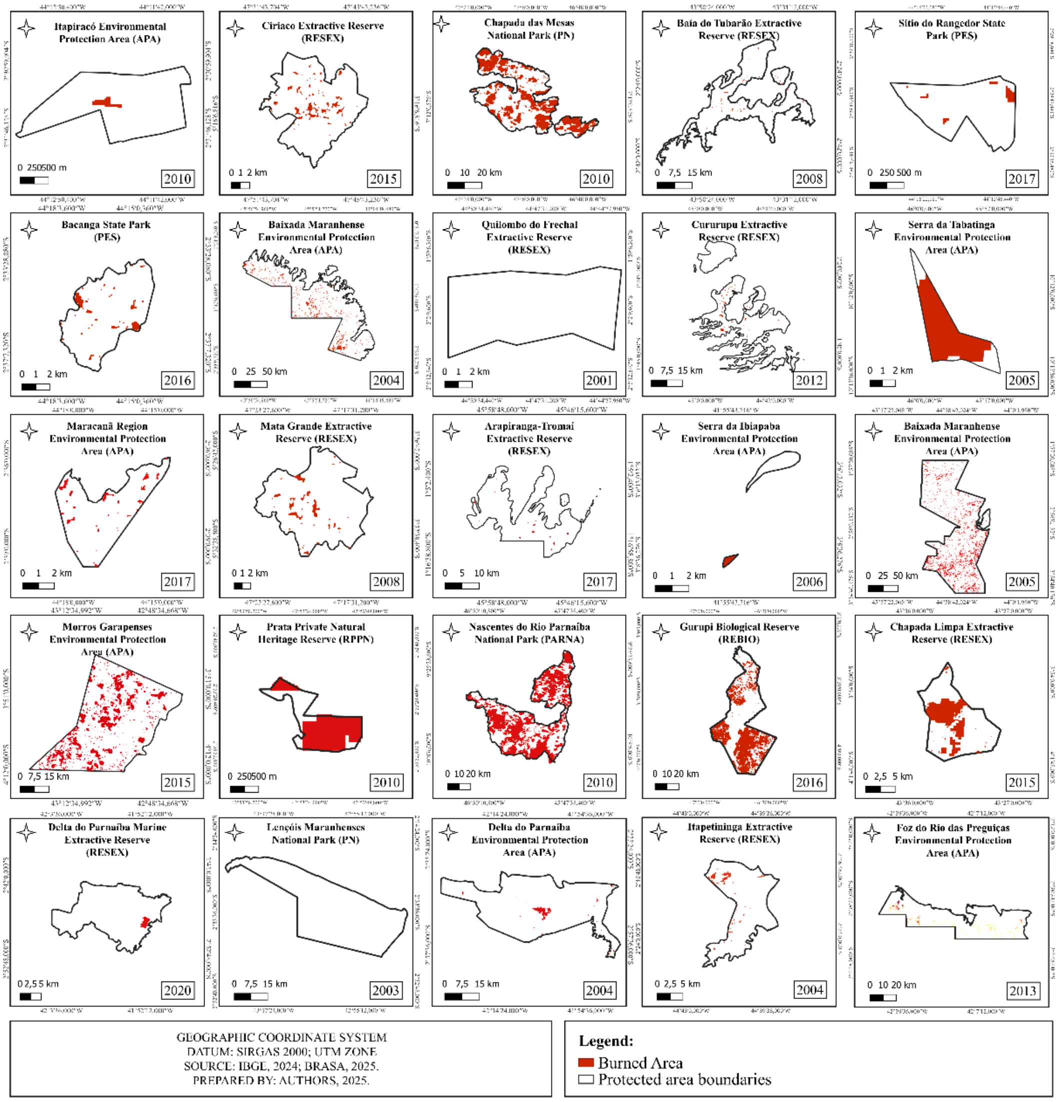
Within the Amazon biome, the Gurupi BR presented the most critical scenario. During the peak recorded in 2016, the unit had 114,771 ha affected by fire, representing 42.3% of its total area. In contrast, wetland and coastal areas demonstrated lower susceptibility. In the Cerrado, the Chapada das Mesas National Park (SP) recorded its highest peak in 2010, with 66,266 ha burned, representing 41.4% of its territorial extension. In proportional terms, the Prata Private Natural Heritage Reserve SU presented the highest value of the series, with 64.4% of its total area affected in the same year, despite its small absolute extent (Figure 5).

Fig 5: Spatial distribution of the years of highest burned area severity in the Protected Areas of Maranhão (2001 - 2020).



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Fire Recurrence Patterns

In the Amazon–Cerrado transition zone, the Ciriaco ER (SU), with a total area of 8,106.75 ha, recorded its highest burning peak in 2015, with 404.44 ha affected, representing 4.99% of the territory in a single year. According to Table 2, the unit exhibits a low recurrence pattern, with 98.27% of the burned area affected by only 1 to 3 events over the 20-year period, while only 1.72% showed medium recurrence (4 to 7 events).

Table 2: Percentage distribution of fire recurrence classes (1–3, 4–7, 8–11, and ≥12 events) and total burned area (ha) in Protected Areas of Maranhão (2001–2020).

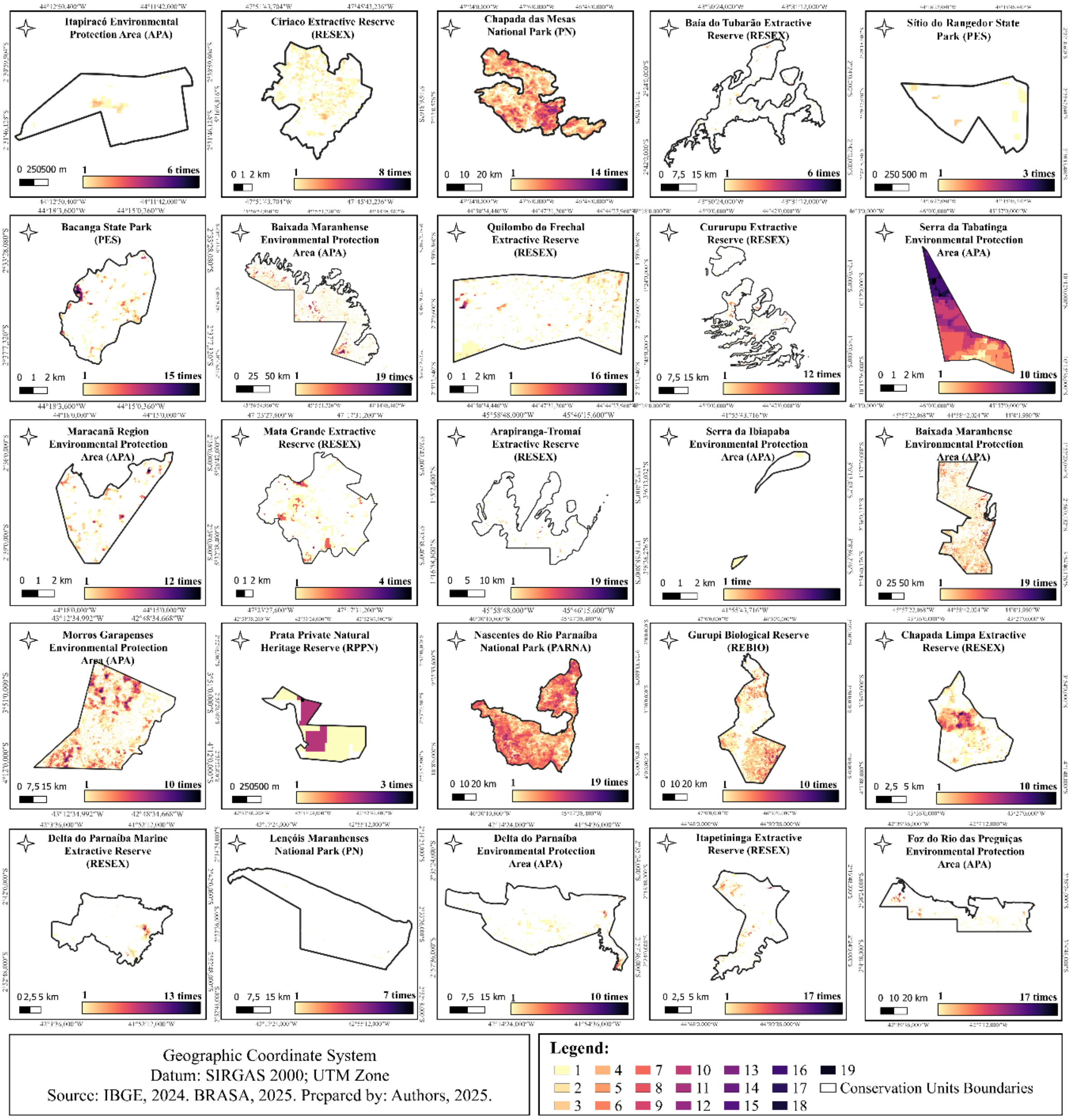
Protected Areas	1 a 3 (%)	4 a 7 (%)	8 a 11 (%)	≥12 (%)	Total Burned Area (ha)
Itapiracó EPA	95.10%	4.90%	0,00%	0.00%	23.61
Ciriaco ER	98.27%	1.72%	0,01%	0.00%	3,299.13
Chapada das Mesas NP	46.00%	41.07%	11,98%	0.96%	612,093.93
Baía do Tubarão ER	90.79%	7.79%	1,15%	0.28%	4,937.86
Sítio do Rangedor State Park	100.00%	0.00%	0,00%	0.00%	10.16
Bacanga State Park	79.67%	12.27%	5,33%	2.73%	1,200.64
Reentrâncias Maranhenses EPA	79.32%	13.53%	4,74%	2.42%	603,891.95
Quilombo do Frechal ER	94.30%	4.39%	1,07%	0.26%	2,438.38
Cururupu ER	88.55%	10.89%	0,56%	0.00%	10,999.78
Serra da Tabatinga EPA	28.51%	55.16%	16,32%	0,00%	10,129.82
Região do Maracanã EPA	88.40%	10.01%	1.39%	0.20%	681.03
Mata Grande ER	99.87%	0.13%	0.00%	0.00%	2,306.76
Arapiranga–Tromaí ER	88.43%	8.91%	1.95%	0.72%	1,725.67

Serra da Ibiapaba EPA	100.00%	0.00%	0.00%	0.00%	42.93
Baixada Maranhense EPA	77.80%	18.64%	3.01%	0.55%	2,050,868.67
Morros Garapenses EPA	73.72%	21.80%	4.21%	0.26%	339,296.15
Prata RPPN	100.00%	0.00%	0.00%	0.00%	100.74
Nascentes do Rio Parnaíba NP	25.15%	58.80%	15.71%	0.33%	1,809,825.03
Gurupi BR	91.84%	8.07%	0.07%	0.00%	313.348,80
Chapada Limpa ER	84.35%	15.21%	0.44%	0.00%	10,709.93
Delta do Parnaíba Marine ER	87.97%	10.69%	1.17%	0.18%	2,407.60
Lençois Maranhenses NP	98.19%	1.81%	0,00%	0.00%	368.54
Delta do Parnaíba EPA	95.45%	4.37%	0.17%	0.02%	13,016.03
Itapetininga ER	88.79%	9.75%	0.79%	0.62%	2,841.32
Foz do Rio das Preguiças EPA	88.78%	8.13%	2.49%	0.59%	31,363.61

Organized by: Authors, 2026.

Within the Cerrado biome, the Nascentes do Rio Parnaíba National Park (SP) presented the largest cumulative burned area (>1.8 million ha). This value exceeds the total area of the protected area (1.113 million ha) because it represents the cumulative burned area, which accounts for fire recurrence over time. In this approach, the same pixel burned in different years is counted multiple times, reflecting the repeated occurrence of fire events in the same location. Of this total, 74.51% showed a recurrence of 4 to 11 fire events. In the Chapada das Mesas National Park (SP), 11.98% of the affected area reached 8 to 11 events, with a significant peak recorded in 2010. In peri-urban areas, such as the Sítio do Rangedor State Park (SP), 100% of the burned area maintained a low recurrence (1 to 3 events) (Figure 6).

Fig 6: Spatial distribution of fire recurrence in the Protected Areas of Maranhão.



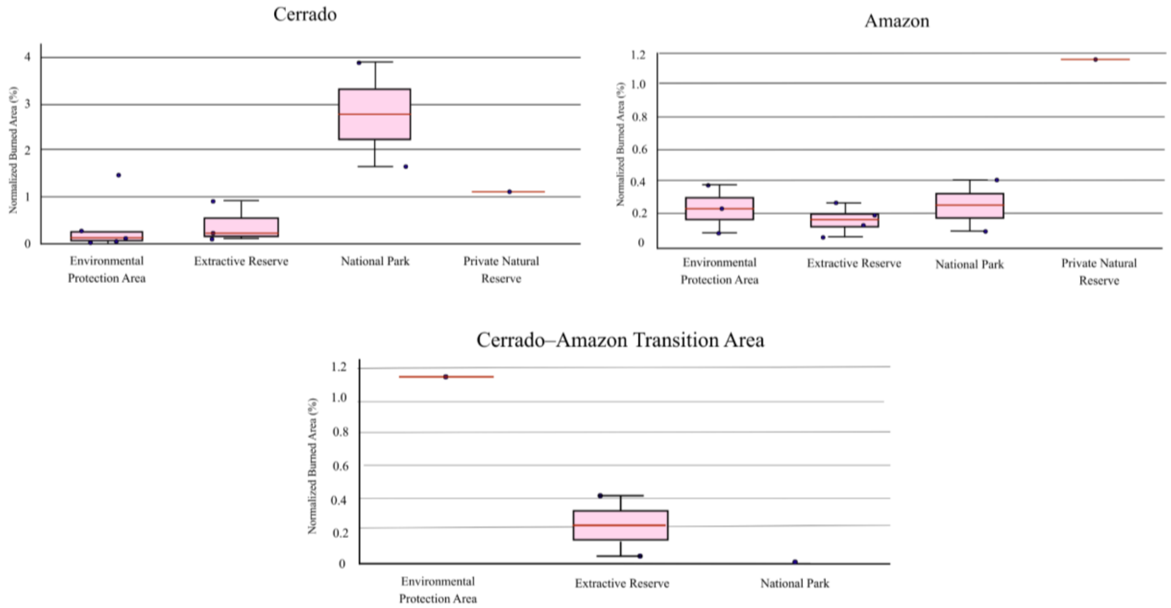
Organized by: Authors, 2026.

In the Amazon biome, the Gurupi Biological Reserve (SP), despite recording the highest annual peak of burned area in absolute, is characterized by a predominance of low recurrence (1 to 3 events), with only isolated records of up to 10 events. Similarly, in the Baixada Maranhense EPA (SU), recurrence was mainly concentrated in the class of up to 3 events per polygon, although isolated registrations reached 19 occurrences

Effectiveness of Legal Protection and Jurisdictions

The Mann-Whitney test revealed a statistically significant difference only in the Cerrado (U=18.0; p=0.036), where Strict Protection units exhibited lower burned area proportions than Sustainable Use areas. No significant differences between management categories were detected in the Amazon (p=0.267) or Transition (p=0.500) biomes. Administrative jurisdiction (federal vs. state) showed no significant effect across any biome (Amazon: p=1.000; Transition: p=0.500; Cerrado: p=0.909). Similarly, Kruskal-Wallis tests comparing specific PA categories (EPAs, ERs, BRs, PNHRs, Parks) found no significant differences in burned area extent (Amazon: H=2.95, p=0.399; Transition: H=2.70, p=0.259; Cerrado: H=5.48, p=0.140), indicating that normative distinctions between typologies do not translate into differential fire outcomes.

Fig 7: Distribution of normalized burned area (%) in Protected Areas, according to management categories, in the Cerrado, Amazon, and Transition zone biomes.

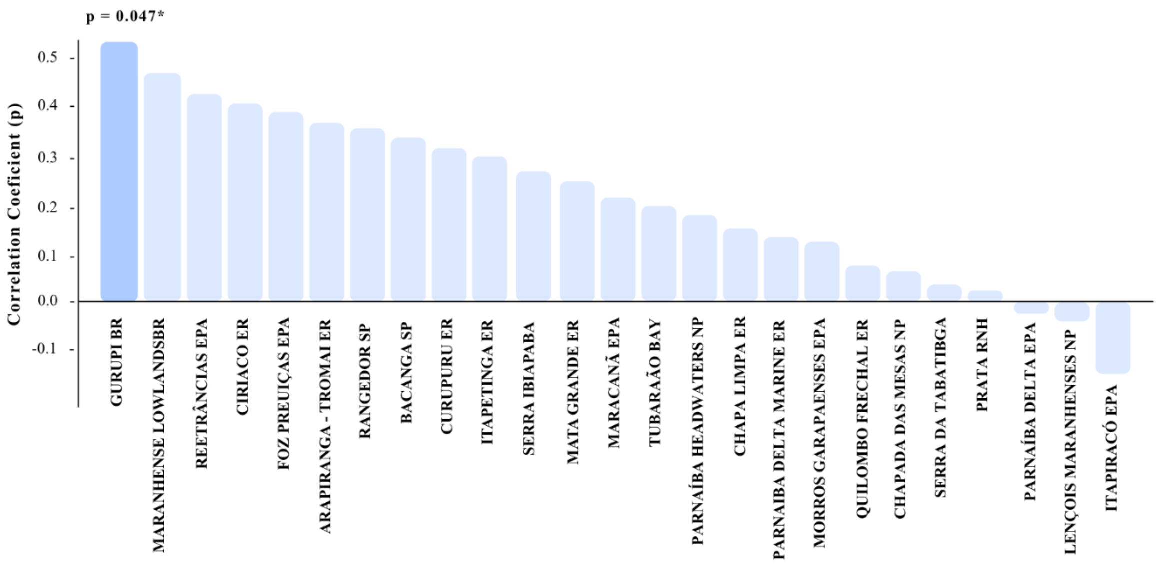


Organized by: Authors, 2026.

Climatic Influence (ENSO)

The Spearman correlation (Figure 8) was applied to evaluate whether fire dynamics respond to external climate drivers, specifically the ONI. The results indicated that for the majority of the Protected Areas, fire extent is not directly governed by ENSO phases (p>0.05), suggesting that local factors and anthropogenic pressures may override global climatic signals.

Fig 8: Spearman correlation (ρ) between annual burned area and the Oceanic Niño Index (2001–2020).



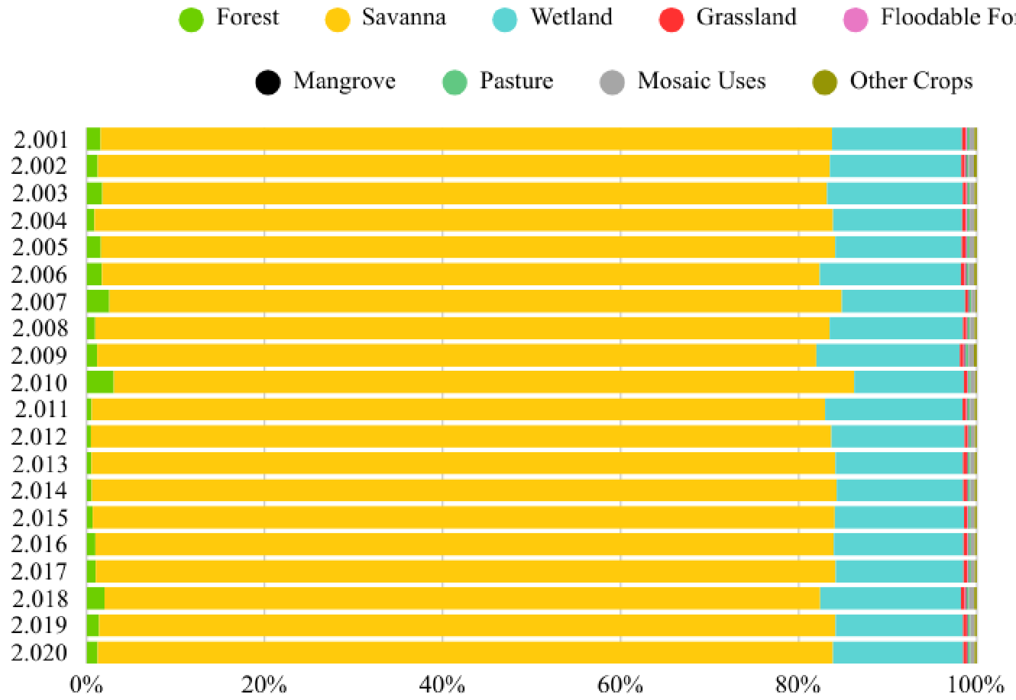
Organized by: Authors, 2026.

Nevertheless, a notable exception was observed for the Gurupi Biological Reserve, which exhibited a significant positive correlation (ρ=0.58; p=0.007). This finding demonstrates that while most PAs show independence from large-scale oscillations, specific areas of high ecological sensitivity remain highly vulnerable to climate-induced drought.

Fire Association with Land Use and Land Cover (LULC)

From this perspective, in the Cerrado biome, fire has predominance in natural areas, with the Savanna Formation class accounting for approximately 78.9% of the total burned area during the 2010 peak. PAs such as the Chapada das Mesas National Park and the Nascentes do Rio Parnaíba National Park concentrated high burned area values, with the latter being the unit with the largest cumulative burned area throughout the time series (Figure 9).

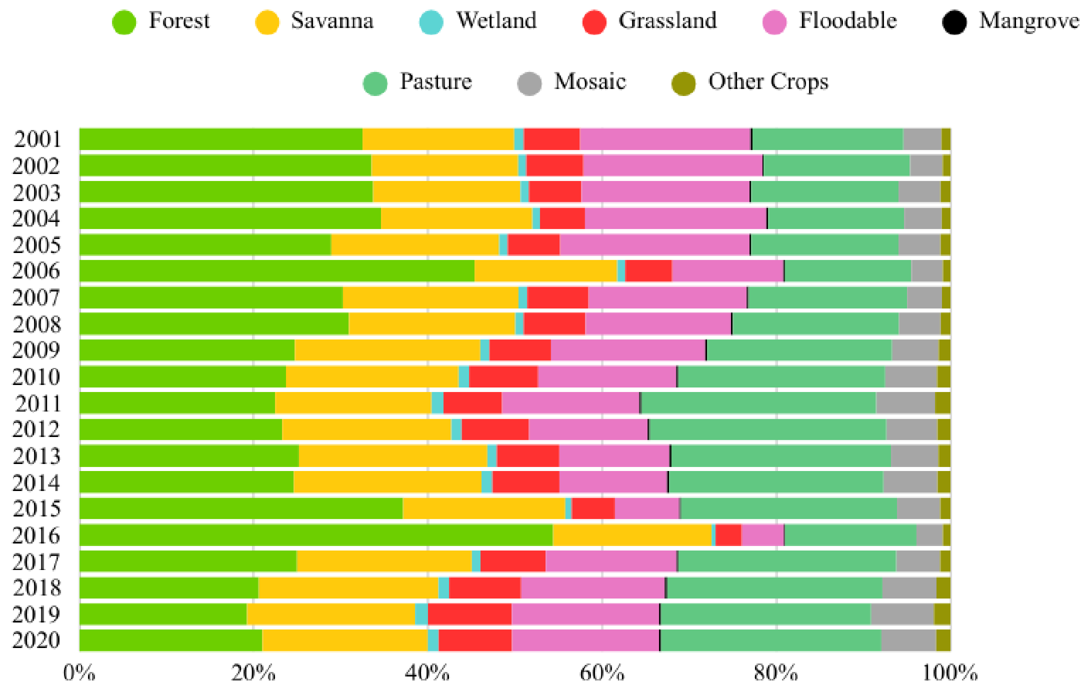
Fig 9: Annual burned area (ha) by Land Use and Land Cover classes in the Cerrado biome, Maranhão (2001–2020).



Organized by: Authors, 2026.

In the Maranhão Amazon in 2016, the Forest Formation class accounted for 68.1% of the burned area in the biome, with a notable impact on the Gurupi Biological Reserve, where 42.3% of the territory was affected in a single year. Additionally, protected areas associated with humid and coastal environments, such as the Reentrâncias Maranhenses Environmental Protection Area and the Baixada Maranhense Environmental Protection Area, recorded fire occurrences in the Flooded Forest and Wetlands classes, which together accounted for 6.6% of the burned area (Figure 10).

Fig 10: Annual burned area (ha) by Land Use and Land Cover classes in the Amazon biome, Maranhão (2001–2020).

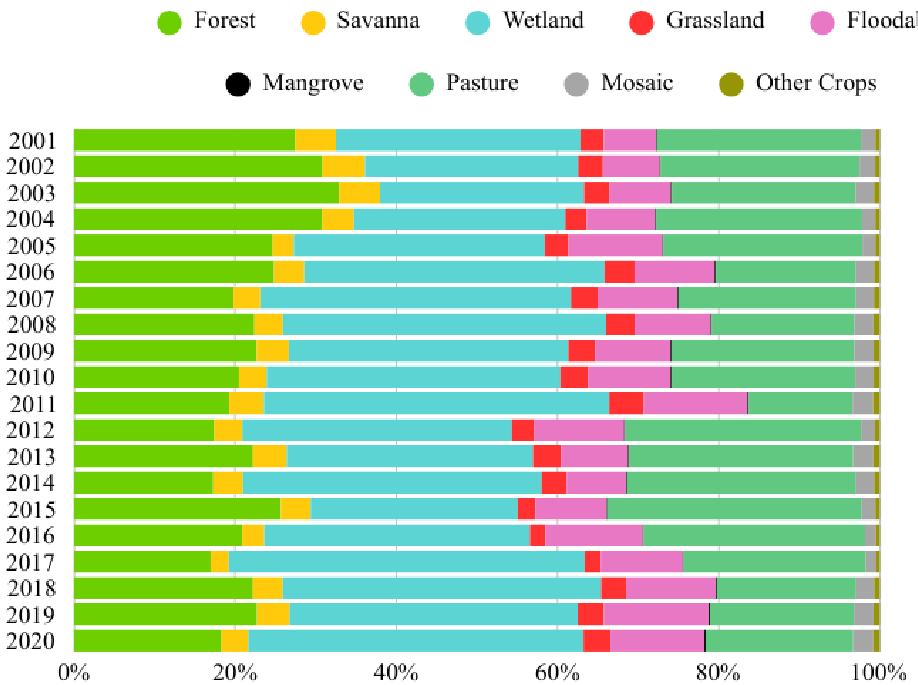


Organized by: Authors, 2026.

Finally, within the Amazon–Cerrado Transition Zone, the Pasture and Mosaic of Uses classes reached up to 30% of the burned area during dry years, with Conservation Units such as the Ciriaco Extractive Reserve

(84.75% Amazon and 15.25% Cerrado) and the Baía do Tubarão Extractive Reserve (49.86% Amazon and 8.50% Cerrado) showing fire records distributed across both domains (Figure 11).

Fig 11: Annual burned area (ha) by Land Use and Land Cover classes in the Transition biome, Maranhão (2001–2020).



Organized by: Authors, 2026.

DISCUSSION

What are the implications of burned area detection differences between products?

The comparison between BRASA and GABAM reveals a systematic underestimation of burned areas in Maranhão's Protected Areas by global datasets. BRASA detected more than five times the area mapped by GABAM over the 2001–2020 period, indicating that previous assessments may have significantly understated the true magnitude and spatial heterogeneity of fire regimes in the Amazon–Cerrado transition. This enhanced detection capacity provides a more accurate empirical foundation for evaluating PA effectiveness, informing fire management, and guiding adaptive governance in this region of intense anthropogenic and climatic pressures

Does protected area regulation matter for fire occurrence?

Although Brazil has significantly expanded its PAs network over recent decades, their establishment “on paper” does not ensure immunity from anthropogenic disturbances, particularly fire (Rylands and Brandon 2005; Matos et al. 2020). The results presented here reinforce this structural limitation by demonstrating that most PAs in Maranhão operate as ecologically permeable systems, where legal status alone is insufficient to decouple fire regime from regional land-use pressures and climatic variability.

The absence of statistically significant differences between SP and SU categories in the Amazon and Amazon–Cerrado Transition biomes directly challenges the normative expectations of the SNUC. In theory, SP units should exhibit greater resistance to fire due to restricted access and the absence of permanent human occupation (Silva et al. 2025; Roque et al. 2018). However, the empirical evidence suggests that contextual factors, particularly geographic location, landscape configuration, and institutional isolation, override formal management distinctions. A substantial portion of the analyzed PAs is embedded within the eastern segment of the so-called Arc of Deforestation, where rapid land conversion driven by agricultural expansion establishes a regional fire-prone matrix (Fearnside 2017; Barlow et al. 2018).

Within this belt of intense anthropogenic pressure, fire serves as a low-cost, operationally efficient tool for clearing recently deforested areas and maintaining productive systems, especially pastures (Carmenta et al. 2018; Campanharo et al. 2019; Dutra et al. 2023). The spatial proximity between protected territories and active agricultural frontiers generates a persistent edge effect, in which fire occurrence and recurrence within PAs are largely determined by surrounding land-use intensity rather than by internal management rules (Silvério et al. 2022; Canova et al. 2023). Consequently, the lack of statistical differentiation among PA categories in the Amazon biome reflects a high degree of territorial permeability, integrating these units into the broader regional fire regime regardless of their administrative sphere or legal typology (Alencar et al. 2015).

In contrast, the statistically significant difference observed in the Cerrado, where SP exhibited lower proportions of burned area, suggests that, in savanna ecosystems, stricter access control and limitations on direct land use may partially reduce ignition probability (Eloy et al. 2019). Nevertheless, this apparent protective effect remains fragile. The Maranhão Cerrado is situated within the MATOPIBA frontier (an acronym for the states of Maranhão, Tocantins, Piauí, and Bahia), a region currently identified as one of Brazil's most critical hotspots for pronounced warming and drying trends (Marengo et al. 2022). Landscape fragmentation and recurrent fire in surrounding areas create a highly flammable mosaic, allowing external ignitions to spread into protected areas. As a result, even SP units such as National Parks remain embedded in a "fire landscape," where fuel continuity facilitates large-scale fire events that exceed historical ecological regimes and threaten biodiversity adapted to lower-frequency fire cycles ((Pivello 2011; Rodrigues and Fidelis 2022).

Challenges and opportunities for wildfire prevention in Maranhão protected areas

The persistence of high burning rates and statistical similarity between SP and SU units reveal a disconnect between legal frameworks and territorial dynamics, a contradiction made more relevant by the recent National Integrated Fire Management Policy (PNMIF – Federal Law No. 14,944/2024), which shifts from repressive to adaptive fire governance (Brasil 2024). Historically, "zero-fire" strategies have proven insufficient to shield PAs from external pressures, particularly within the Arc of Deforestation and MATOPIBA frontier, where land-use expansion and anthropogenic ignitions intensify fire incidence regardless of legal status (Eloy et al. 2019; Silva et al. 2020). This challenge is compounded by climatic variations that expand the window of risk for uncontrolled fires.

Although a significant correlation between burned area and ONI was detected only for the Gurupi Biological Reserve, this finding indicates a broader mechanism of climatic facilitation. Severe ENSO-related droughts increase water deficits and biomass flammability, weakening fire's dependence on recent deforestation (Aragão et al. 2018). In Maranhão, climate oscillations act not as primary ignition drivers but as amplifiers that intensify the spread and severity of predominantly anthropogenic fires.

This interaction between climatic stress and land-use practices is particularly evident in the Amazon–Cerrado transition zone, where reduced ecosystem resilience creates a temporal "flammability window" that favors the escape of agricultural fires into protected areas (Dos Reis et al. 2021; De Aquino Aragão et al. 2023). Under such conditions, traditional management burns can escalate into high-magnitude wildfires, especially during years of extreme drought (Libonati et al. 2022). The strong spatial association between burned areas and Pasture and Mosaic of Uses classes confirms that fire regimes within Maranhão's PAs are intrinsically linked to regional production cycles. Such linkages are particularly alarming when these fires cross into more humid, fire-sensitive environments.

In the Amazon biome, the extensive impact on Forest Formations and wetlands signals severe ecological degradation. Tropical humid forests are fire-sensitive systems where fire penetration initiates positive feedback loops: canopy mortality increases light and wind penetration, dries the understory, and accumulates dead biomass, enhancing susceptibility to recurrent fires (Cochrane et al. 1999; Zhang et al. 2023). This process now surpasses deforestation as a dominant pathway of large-scale forest degradation in the Amazon (Matricardi et al. 2020). Fire detection in seasonally flooded ecosystems, such as the Baixada Maranhense wetlands, indicates the collapse of natural moisture barriers under climatic and anthropogenic stress, placing biodiversity refugia under critical threat (Schöngart et al. 2017).

Given these vulnerabilities, effective protection requires shifting from reactive fire control toward evidence-based territorial governance. Integrated Fire Management emerges as a central strategy, particularly in Cerrado and Transition PAs. Federal Law No. 14,944/2024 recognizes the ecological inadequacy of total fire exclusion in savannas, where fuel accumulation can increase fire severity. Prescribed early dry-season burns, as implemented in Chapada das Mesas National Park, promote landscape heterogeneity, reduce fuel continuity, protect fire-sensitive forest patches, and mitigate extreme fire behavior during severe drought years (Da Veiga et al. 2024).

Equally critical is strengthening buffer zones and integrating PAs into surrounding rural landscapes. Given that ignition sources are predominantly external, high-resolution monitoring systems such as the BRASA product should support not only suppression efforts but also preventive planning, including strategic firebreak placement and negotiated burning calendars with local producers. As highlighted by Silva-Junior et al. (2020), governance frameworks that anticipate critical drought conditions are more effective at preventing the leakage of management fires into protected territories.

At the institutional level, long-term PA resilience depends on sustained investments ensuring permanent fire brigades, technological infrastructure, and operational continuity. Conservation effectiveness requires financial stability and trained personnel to avoid a "crisis response" model restricted to peak fire seasons (Rocha and Nascimento 2022). Effective management plan implementation is fundamental for translating normative SP/SU distinctions into tangible ecological outcomes. However, this institutional strengthening must be integrated into a broader territorial perspective, as PA stability is inextricably linked to surrounding private landscape management.

MapBiomas data indicate that between 2001 and 2020 Maranhão experienced extensive landscape conversion, with native vegetation declining from 24.7 to 20.6 million hectares. As the protected network covers only 9 million hectares, over half of remaining native vegetation lies outside PAs, mainly on private lands as Legal Reserves or Permanent Preservation Areas. This underscores private properties' critical role in sustaining regional ecosystem services, soil stability, biodiversity corridors, and the "biotic pump" supporting rainfall production, which underpin MATOPIBA productivity, where soybean cultivation expanded >400% (195,242 to nearly 1 million hectares). However, this rapid expansion has reduced habitat continuity and driven structural landscape changes.

The expansion of anthropogenic areas, particularly the nearly 3 million hectares of pasture added since 2001, has created a fragmented landscape that facilitates fire spread across property boundaries. This fragmentation increases the edge-to-interior ratio of remaining forest patches, making them more susceptible to microclimatic drying and the lateral encroachment of agricultural fires. Consequently, effective conservation in Maranhão requires governance models that move beyond the "paper protection" of PAs and actively engage with the private sector through Landscape-Scale Management. Finally, strategic prioritization should focus on areas identified as chronic fire nuclei through recurrence mapping. In areas where disturbance frequency exceeds vegetation's natural regenerative capacity, passive protection must be complemented by active restoration initiatives. In the Maranhão Amazon, the recovery of canopy structure is particularly critical for reestablishing understory microclimatic conditions and restoring natural fire resilience.

CONCLUSION

This study demonstrates that PAs in Maranhão are not ecologically isolated but embedded in regional fire dynamics driven by land-use and climate. Fire occurrence is shaped by external pressures, proximity to agricultural frontiers and edge effects, with anthropogenic ignitions amplified by ENSO-related climate anomalies during drought years. In the Cerrado, lower burned area in Strict Protection units suggests access restrictions may reduce ignition, yet this effect remains fragile. These areas are embedded within the flammable MATOPIBA landscape, where fragmentation and recurrent fires expose even protected units to high-intensity events.

From a policy perspective, results highlight the inadequacy of reactive fire management. Effective conservation requires institutionalizing Integrated Fire Management (IFM) in Cerrado and transition zones, strengthening buffer zones, and coordinating governance beyond PA boundaries. High-resolution monitoring should inform planning, early warning systems, and negotiated burning calendars with local stakeholders. Ultimately, PA effectiveness depends on sustained investments in governance, infrastructure, and long-term planning. Translating legal protection into ecological outcomes requires adaptive, preventive, and regionally integrated fire policies under accelerating climate change.

DATA ACCESSIBILITY STATEMENT

The data supporting the findings of this study are available from public repositories as follows. The BRASA burned area product, the integrated multi-sensor burned area dataset used in this study, is available at the Zenodo repository: https://zenodo.org/records/18342645 (Leão et al., 2023). Additional information and access to the complete geospatial collection can be obtained through the MapFire platform: https://www.mapfire.info/. Protected Areas boundaries: official boundaries of federal and state Protected Areas in Maranhão were obtained from the Brazilian Ministry of the Environment (MMA) and the Chico Mendes Institute for Biodiversity Conservation (ICMBio), available at: https://www.gov.br/icmbio/pt-br/assuntos/mapas-e-sistemas-de-informacao.

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Supplementary Materials

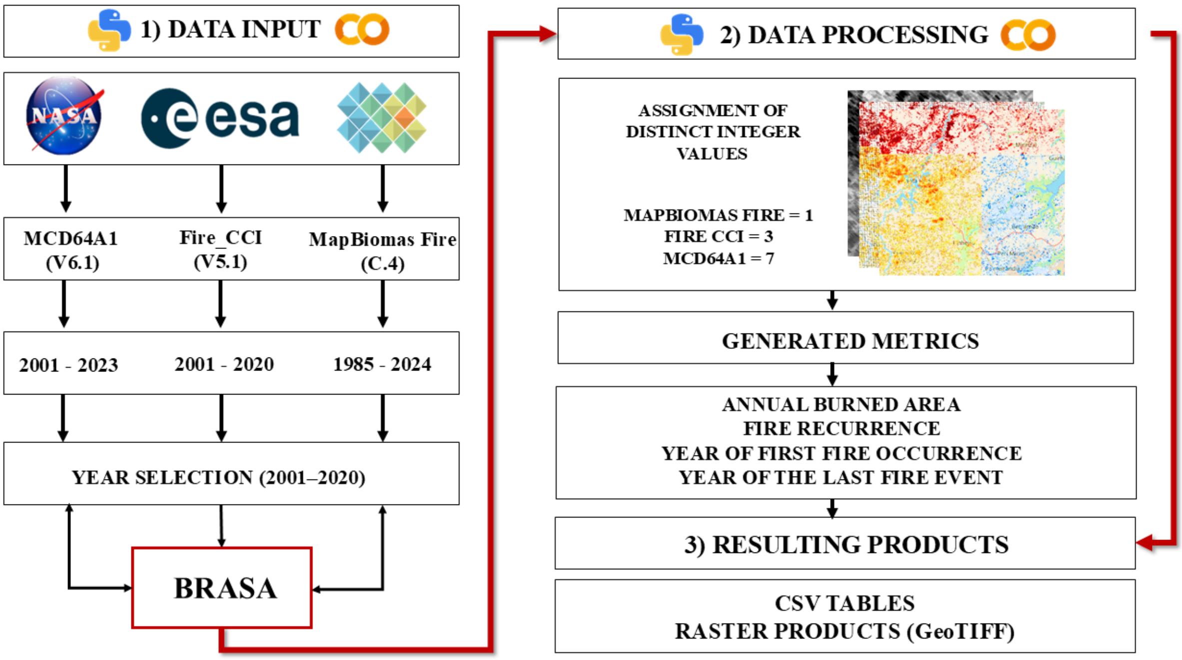
Table 1: Characteristics of state and federal Protected Areas (PAs) in Maranhão.

Protected Area	Area (ha) (% of total)	Jurisdiction	Biome %	Group
Baixada Maranhense Environmental Protection Area	1.775.035 (19.71%)	State	Amazon (99,07%); Cerrado (0,93%)	SU
Foz do Rio das Preguiças Environmental Protection Area	269.684 (2.99%)	State	Cerrado (100%)	SU
Região do Maracanã Environmental Protection Area	1.831 (0.02%)	State	Amazon (100%)	SU
Reentrâncias Maranhenses Environmental Protection Area	2.680.910 (29.78%)	State	Amazon (100%)	SU
Itapiracó Environmental Protection Area	322 (0.003%)	State	Amazon (100%)	SU
Morros Garapenses Environmental Protection Area	234.768 (2.60%)	State	Cerrado (100%)	SU
Bacanga State Park	2.973 (0.03%)	State	Amazon (100%)	SP
Sítio do Rangedor State Park	121 (0.001%)	State	Amazon (100%)	SP

Delta do Parnaíba Environmental Protection Area	309.594 (3.43%)	Federal	Cerrado (100%)	SU
Serra da Ibiapaba Environmental Protection Area	1.628.450 (18.09%)	Federal	Cerrado (100%)	SU
Serra da Tabatinga Environmental Protection Area	41.779 (0.46%)	Federal	Cerrado (100%)	SU
Chapada das Mesas National Park	159.953 (1.77%)	Federal	Cerrado (100%)	SP
Nascentes do Rio Parnaíba National Park*	1.113.217 (12.36%)	Federal	Cerrado (100%)	SP
Lençóis Maranhenses National Park*	156.608 (1.73%)	Federal	Amazon (0,11%); Cerrado (93,95%)	SP
Gurupi Biological Reserve	271.197 (3.01%)	Federal	Amazon (100%)	SP
Arapiranga-Tromaí Extractive Reserve*	34.982 (0.38%)	Federal	Amazon (19,83%)	SU
Chapada Limpa Extractive Reserve	11.973 (0.13%)	Federal	Cerrado (100%)	SU
Baía do Tubarão Extractive Reserve*	149.928 (1.66%)	Federal	Amazon (49,86%); Cerrado (8,50%	SU
Cururupu Extractive Reserve*	86.759 (0.96%)	Federal	Amazon (49,01%)	SU
Ciriaco Extractive Reserve	8.106 (0.09%)	Federal	Amazon (84,75%); Cerrado (15,25%)	SU
Itapetininga Extractive Reserve	15.692 (0.17%)	Federal	Amazon (100%)	SU
Delta do Parnaíba Marine Extractive Reserve	27.022,07 (0.30%)	Federal	Cerrado (100%)	SU
Mata Grande Extractive Reserve	11.431 (0.12%)	Federal	Cerrado (100%)	SU
Quilombo do Frechal Extractive Reserve	9.338 (0.10%)	Federal	Amazon (100%)	SU
Prata Private Natural Heritage Reserve	90 (0.001%)	Federal	Cerrado (100%)	SU

Source: IBGE (2024); ISA (2024); BRASIL (2024).

Fig 2: Flowchart of the processing steps for generating the BRASA burned area product (adapted from Leão et al. 2023).



Organized by: Authors, 2026.