Directional Centroid Trajectories Reveal Shifting Fire Activity Across Brazilian Biomes

Author

Mario Barroso Ramos Neto (Ramos-Neto, M.B.)

The Nature Conservancy

Brasilia, Brazil

Email: mario.barroso@tnc.org

ORCID: https://orcid.org/0000-0001-5890-0536

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All preregistration materials, derived datasets, and analysis code associated with this work are openly available on the Open Science Framework (OSF; DOI: 10.17605/OSF.IO/WA326).

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ABSTRACT

We utilized directional centroid trajectories to examine how Brazil's fire regimes in natural vegetation and anthropogenic land use have spatially reorganized over the last four decades. Annual area-weighted centroids were derived separately for natural and anthropogenic burned patches from the MapBiomas Fire Collection 4 (1985–2024), and their interannual displacements were quantified using great-circle distance and azimuth. Centroids associated with natural vegetation and anthropogenic use formed persistently distinct spatial clusters, with a mean separation of 313 km and low kernel overlap (KOI = 0.17), indicating structurally different spatial domains of fire activity. Despite this separation, most interannual centroid displacements were directionally 'aligned' or 'moderately aligned', with truly 'divergent' years being rare and directionally scattered. Major climate anomalies (El Niño, La Niña, ZCAS-related droughts) showed no consistent association with directional divergence. Biome-level burned-area deltas revealed coherent but noisy patterns by 'Attraction Region', suggesting that centroid trajectories integrate multi-biome redistributions of fire without a single dominant driver. An exceptional convergence of natural and anthropogenic centroids in 2024 was linked to a record increase in burned natural vegetation in the Amazon, illustrating how extreme drought can temporarily homogenize otherwise distinct fire regimes.

This manuscript is a non-peer-reviewed preprint posted on EarthArXiv. Data, code, and preregistration are available at the Open Science Framework (OSF; DOI: 10.17605/OSF.IO/WA326).

INTRODUCTION

Centroid-based metrics are sometimes used in spatial analysis because they distill complex geographic patterns into interpretable measures of central tendency and displacement. In urban studies, for example, centroid trajectories have been used to track long-term shifts in the spatial distribution of population and infrastructure, revealing directional trends in metropolitan expansion and socio-spatial reorganization (Alvarez-Sanches et al., 2020; Fan et al, 2025). Similar approaches have been applied in ecology, particularly in metapopulation and species-distribution modeling, where annual or seasonal centroid shifts capture changes in habitat use, dispersal patterns, and range contraction or expansion under environmental change (Watts et al., 2013). Across these domains, centroid trajectories serve as a synthetic indicator of broad-scale spatial reorganization, revealing directional tendencies that emerge from many individual patches, events, or observations. Building on this tradition, we employ a centroid-based framework to examine how Brazil's fire regimes—both natural and anthropogenic—evolve spatially over time.

Understanding long-term fire dynamics in Brazil requires reconciling two interacting dimensions: the ecological variation among biomes and the socioeconomic forces that shape ignition patterns. Fire regimes in Brazil exhibit firm spatial heterogeneity driven by differences in vegetation structure, fuel continuity, climate seasonality, and land-use intensity (Pivello, 2011; Pivello et al., 2021; Oliveira et al., 2022). In the Amazon, despite some critical Cerrado enclaves, fires are almost entirely anthropogenic and intensely concentrated along the 'Arc of Deforestation' (Amazon deforestation frontier, a broad, crescent-shaped frontier of agricultural expansion that runs along the southern and eastern edges of the Brazilian Amazon, from Maranhão through Tocantins, Pará, Mato Grosso, and Rondônia towards Acre), where fragmentation and deliberate ignition promote recurrent fire activity even in typically non-flammable forests (Alencar et al., 2020; Oliveira et al, 2022). In contrast, the Cerrado exhibits a natural fire-adapted savanna vegetation with frequent burning under both natural and human ignition sources, while the Caatinga, Pantanal, and Atlantic Forest present distinct combinations of climatic sensitivities and fuel behavior (Pivello, 2011).

Superimposed on these biome-level differences are large-scale climatic oscillations such as El Niño, La Niña, the Atlantic Multidecadal Oscillation, and persistent atmospheric blockings that modulate drought intensity and fire weather across regions (e.g., 1997–1998, 2010, 2015–2016, 2023–2024). These anomalies alter the spatial distribution of burned areas at the national scale, potentially shifting the "center of gravity" of fire activity toward different biomes. Anthropogenic pulses — including agricultural expansion in the MATOPIBA region, native pasture renewal cycles in central Brazil, and exceptional events such as the 2019 "Dia do Fogo" along the BR-163 corridor (Caetano, 2021) — further intensify directional shifts in fire occurrence.

Although extensive research has characterized fire determinants at the biome level, less attention has been given to how the spatial position of fire activity shifts over time. Here, we propose a simple but powerful metric: annual centroids of burned patches, derived separately for natural vegetation and anthropogenic land use using 40 years of data from the MapBiomas Fire Collection 4. By tracking the direction and magnitude of centroid movement, we provide the first long-term assessment of how fire activity migrates across Brazilian landscapes. We show that this trajectory-based approach, despite its intentional simplification, reveals striking patterns of coordinated movement that reflect underlying ecological, climatic, and socioeconomic drivers.

In this study, we use directional centroid trajectories to ask four related questions about the long-term geography of fire in Brazil. First, do fires in natural vegetation and in anthropogenic land use occupy persistently distinct spatial domains, as expected from their contrasting ignition sources and fuel structures? Second, are interannual centroid displacements in these two regimes generally directionally coherent, or do they frequently move in divergent directions across the landscape? Third, to what extent do major climate anomalies such as El Niño, La Niña, and ZCAS-related droughts modulate the directional agreement between natural and anthropogenic fire trajectories? Finally, do episodes of directional divergence correspond to systematic shifts in where burned area is redistributed across biomes, as would be expected if centroid movements integrate multi-biome reorganizations of fire activity? By addressing these questions, we aim to show how a simple centroid-based framework can reveal large-scale patterns of spatial reorganization in Brazil's fire regimes that are not easily captured by traditional pixel- or patch-based metrics.

OBJECTIVES AND HYPOTHESES

Our overarching goal was to quantify how fires in natural vegetation and in anthropogenic land uses have occupied geographic space in Brazil over the last four decades, and to assess whether their trajectories respond differently to large-scale climate anomalies. Specifically, we addressed the following hypotheses:

H1 – Persistent spatial separation.

Annual centroids of burned area in Natural Vegetation and Anthropogenic Use form two spatially distinct and consistently separated clusters throughout the 1985–2024 period, rather than oscillating around a common central region.

H2 – Directional structure of trajectories.

Interannual displacement vectors for each regime exhibit non-random directional structure, with natural and anthropogenic centroids following partially distinct preferred directions that reflect underlying biogeographical and land-use gradients.

H3 – Climate-related directional divergence.

The angular difference between natural and anthropogenic trajectories is larger during years influenced by major climate anomalies (El Niño, La Niña, or SACZ/ZCAS-related droughts) than during climatically neutral years, indicating a stronger decoupling of fire regimes under anomalous conditions.

H4 – Consistency with biome-level burned-area changes.

Periods with strong directional divergence between regimes are associated with asymmetric changes in burned areas among biomes (e.g., Cerrado, Amazon, Pantanal), such that centroid shifts are coherent with which regions gain or lose relative fire activity.

RESULTS

Spatial patterns of natural and anthropogenic fire centroids

The annual centroids formed two clearly distinct spatial clusters, one associated with natural-vegetation fires and the other with anthropogenic fires (Figure A). This separation is not only visually apparent but is quantitatively supported by multiple metrics. The mean great-circle distance between the centroids of the two regimes over the 40-year period was 313 km (range: 69–504 km), demonstrating a persistent spatial gap even during years of the strongest convergence. Cluster-dispersion analysis further confirmed this pattern: despite considerable within-regime variability, the Dunn Index was low (DI = 0.03), indicating that both regimes occupy broad but non-overlapping spatial domains. Crucially, a kernel density overlap analysis revealed only 17% spatial overlap between the two centroid distributions (KOI = 0.17), meaning that more than four-fifths of the spatial footprint of natural-fire centroids remains distinct from that of anthropogenic ones. Together, these metrics demonstrate that the two fire regimes have consistently maintained separate spatial structures across nearly four decades, in line with H1, reflecting fundamental ecological and socio-environmental differences in the geography of natural and human-driven fire dynamics in Brazil, while maintaining a stable relational structure.

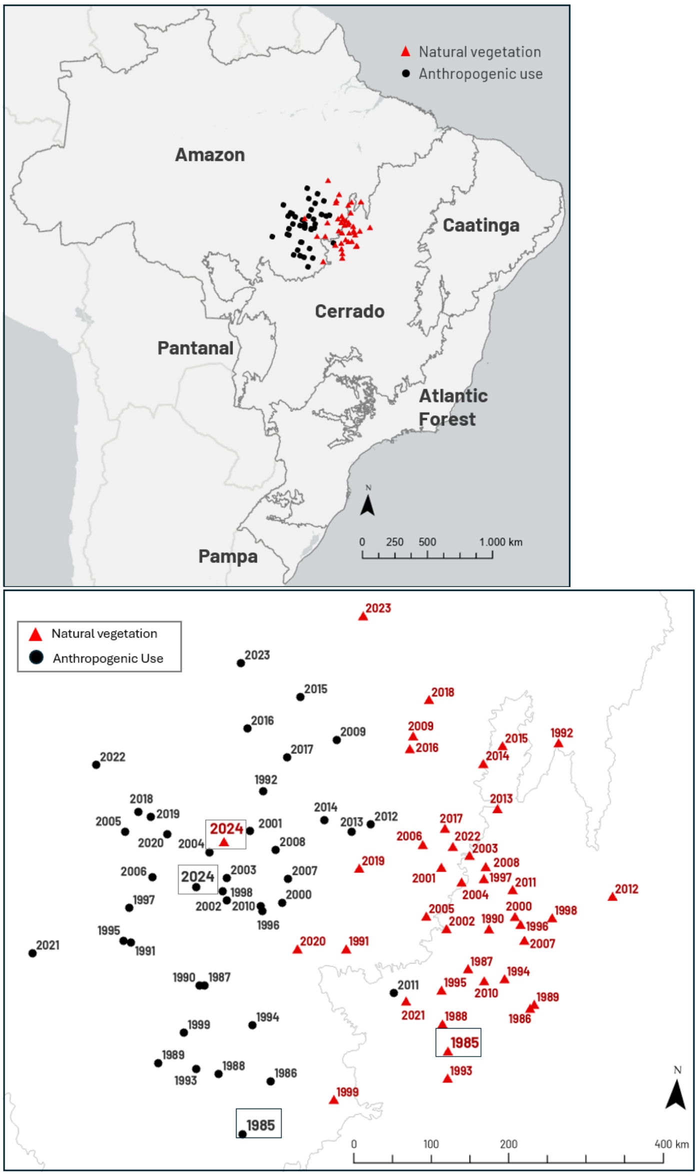

Figure A – Geographic context and spatial distribution of annual fire centroids in natural vegetation and anthropogenic land use (1985–2024).

Each point represents the area-weighted centroid of the total annual burned area by regime (natural vegetation or anthropogenic use), using the MapBiomas Fire Collection 4 dataset. Centroid positions do not indicate the location of specific fires but summarize the spatial balance of fire activity across Brazil each year, computed as the mean coordinate of patch locations weighted by patch area (rook-connected pixel clusters). Red triangles correspond to annual centroids of fires in natural vegetation, and black circles represent centroids of fires in anthropogenic land use. Labels indicate the corresponding year for each centroid; the first year of the series (1985) and the most recent (2024) are highlighted. No connecting lines are shown, preserving the spatial structure of the centroid clouds without visual clutter. The figure illustrates the persistent spatial separation between natural and anthropogenic fire regimes, the long-term east-west displacement pattern, and the exceptional convergence observed in 2024, when both systems exhibited centroids in unusually close spatial proximity.

Interannual centroid displacements and directional variability

Interannual centroid displacements (year t → t+1) show considerable variation in both magnitude and direction for natural and anthropogenic fire regimes (Figure B). Despite this variability, no intense or persistent directional trend is observed within either system. Rather than exhibiting a consistent drift toward a particular region, centroids fluctuate in a pattern that reflects complex, multiscale interactions among vegetation types, land use, and climate variability.

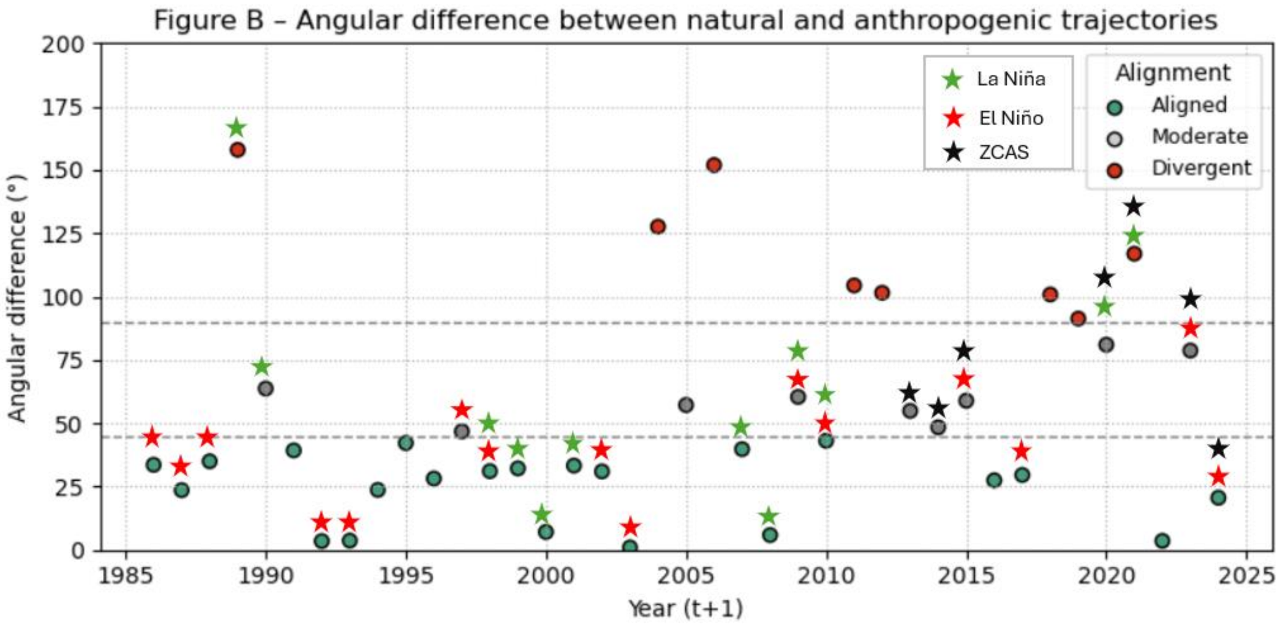

Figure B – Angular difference between natural and anthropogenic centroid trajectories.

Colored stars highlight years affected by significant climate anomalies: El Niño (red), La Niña (green), and years with documented ZCAS-related droughts or atmospheric blockings (black). These climatic markers are presented solely as temporal references, and the results reveal no consistent or systematic correspondence between the occurrence of climate anomalies and the magnitude of directional divergence between natural and anthropogenic fire trajectories.

Directional coherence between the natural and anthropogenic fire systems was evaluated by computing the absolute angular difference between their interannual displacement vectors. Angular differences were then categorized as 'aligned' (<45°), 'moderate' (45–90°), or 'divergent' (>90°). Across the 39-year-to-year intervals, most years fall in the 'aligned' category, indicating that although the two fire systems remain spatially distinct, their interannual shifts often occur in broadly similar directions. This predominance of aligned directions indicates that strong and persistent directional decoupling between regimes is rare, providing only limited support for H2.

Statistical tests did not support any systematic association between climate anomalies and the directional divergence between natural and anthropogenic centroid trajectories. Mean angular differences varied widely within each category (El Niño: 38°, La Niña: 43°, None: 75°), and these distributions were statistically indistinguishable (Kruskal–Wallis H = 5.17, p = 0.160). Similarly, the frequency of 'aligned', 'moderate', and 'divergent' years did not differ across climate conditions (χ^2 = 10.19, p = 0.252). A logistic regression evaluating whether El Niño, La Niña, or ZCAS events increased the probability of divergence failed to converge due to complete separation, indicating the absence of any learnable relationship. These results hold even under a permissive climatic assignment, where anomalies were assumed to influence not only the year in which they peak but also the adjacent two-year transition periods. Taken together, these findings suggest that major climate anomalies do not consistently imprint a directional signal on the relative trajectories of natural versus anthropogenic fire centroids, and H3 was not supported by our data.

The exceptional behavior of 2024

The year 2024 stands out in two respects:

(i) It exhibits one of the smallest angular differences of the entire series, and
(ii) It presents the shortest geographic distance between natural and anthropogenic centroids across all 40 years.

This combination of spatial convergence and directional coherence suggests that the fire activity of 2024 represents an unusual configuration in which the spatial domains of the two fire systems overlap more than in any other year of the record. Because such convergence is not observed in previous climatic extremes — including the severe droughts of 2005, 2010, 2015–2016, or 2023 — the 2024 pattern does not appear to reflect a simple climatic forcing. Its interpretation, therefore, demands a broader contextualization of the biophysical and human drivers, which we elaborate on in the Discussion. In terms of our hypotheses, 2024 represents a transient violation of the otherwise persistent spatial separation described in H1, without providing clear support for H2 or H3.

Biome-level changes in burned area and centroid trajectories (H4)

To evaluate whether directional divergence between natural and anthropogenic fire trajectories (Figure C) is consistent with underlying changes in burned area across biomes (H4), we related angular differences to biome-level variations in burned area for natural vegetation and anthropogenic use (Table 1). Multivariate linear and logistic models, including all biomes as predictors, explained only a modest fraction of the variance in angular difference (R^2 = 0.38, adjusted R^2 = 0.09, F = 1.33, p = 0.26) and in the probability of 'divergent' years (pseudo-R^2 = 0.11, likelihood-ratio p = 0.61), with no individual coefficients reaching statistical significance. However, descriptive summaries by Attraction Region revealed coherent spatial signatures. Periods in which trajectories were attracted towards the Cerrado/Amazon sector showed, on average, positive deltas (use–natural) in Cerrado, Amazon, and Pantanal, and negative deltas in Caatinga and Atlantic Forest, indicating a relative reinforcement of anthropogenic burning in the central–western biomes. In contrast, the Cerrado/Atlantic Forest/Pampa intervals exhibited broadly positive deltas across the Cerrado, Amazon, Caatinga, and Atlantic Forest, and negative deltas in the Pantanal, reflecting a more general intensification of anthropogenic burning as trajectories shifted towards eastern and southern biomes. Cerrado/Caatinga and Cerrado/Pantanal sectors exhibited more mixed patterns, combining negative deltas in some core biomes with positive deltas in neighboring ones. Overall, these patterns suggest that centroid trajectories integrate shifts in the spatial redistribution of burned areas across biomes; however, the statistical signal is weak and noisy, providing only partial support for H4.

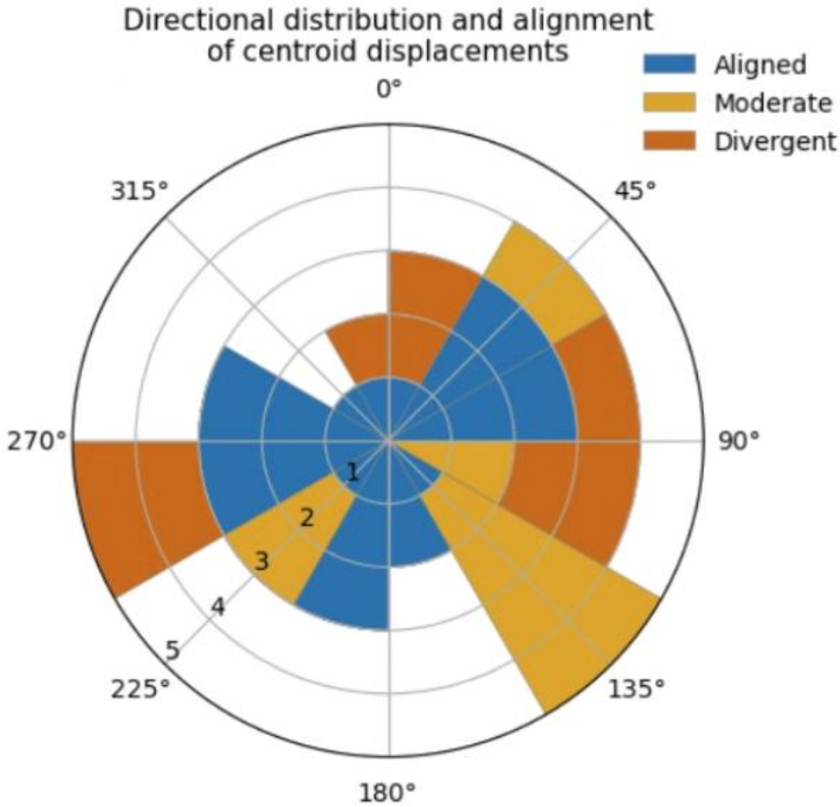

Figure C. Directional distribution and alignment of interannual centroid displacements.

Polar histogram of the directions of natural-vegetation fire centroid displacements between consecutive years (1985–2024). Bars represent the number of year-to-year intervals falling into 30° directional sectors (0° = north, angles increasing clockwise). Colors indicate the angular difference between the natural and anthropogenic displacement vectors in each interval: Aligned (<45°), Moderate (45–90°), and Divergent (>90°). The figure shows that most centroid shifts occur within a limited set of directional sectors and are predominantly aligned or moderately aligned between the two fire regimes, with truly divergent years being comparatively rare and directionally scattered.

Our biome-level analysis provides only partial support for the idea that directional divergence between natural and anthropogenic fire trajectories is tightly driven by where burned area is redistributed across biomes (H4). Multivariate models relating angular divergence or the probability of 'divergent' intervals to biome-level changes in burned area exhibited modest explanatory power, with no individually significant predictors, suggesting that no single biome or regime dominates the signal at the national scale. Nevertheless, the summaries by Attraction Region (Table 1) reveal coherent spatial signatures: intervals in which trajectories are attracted towards the Cerrado/Amazon sector tend to combine relatively stronger anthropogenic burning in Cerrado, Amazon and Pantanal with a greater contribution of natural-vegetation fires in Caatinga and Atlantic Forest, whereas intervals attracted towards the Cerrado/Atlantic Forest/Pampa sector show broadly positive deltas in several eastern and southern biomes. These patterns suggest that centroid trajectories integrate a complex, multi-biome mosaic of natural and anthropogenic fire, rather than responding to simple shifts in a single biome. The weak and noisy statistical signal also highlights the importance of sub-biome heterogeneity in land use and fire management practices, which are likely to modulate centroid behavior in ways that our coarse biome-level summaries cannot fully resolve

Table 1. Mean angular divergence between natural and anthropogenic fire centroid trajectories and biome-level burned-area deltas (use – natural) by Attraction Region. *Each row summarizes all interannual intervals whose centroid trajectories are oriented towards a given sector (Cerrado/Amazon, Cerrado/Caatinga, Cerrado/Atlantic Forest/Pampa, or Cerrado/Pantanal). "Mean angular difference" refers to the average absolute difference between the interannual displacement angles of natural and anthropogenic centroids, and "Divergent years" is the proportion of intervals classified as Divergent (angular difference > 90°). Burned-area deltas (Δ) represent the mean difference between anthropogenic and natural burned areas for each biome over all intervals in a given Attraction Region, expressed in thousands of hectares (×10^3 ha); positive values indicate relatively greater burned area in anthropogenic land use, while negative values indicate relatively greater burned area in natural vegetation.*

Attraction Region	n	Mean angular difference (°)	Divergent years (%)	Cerrado Δ (×10^3 ha)	Amazon Δ (×10^3 ha)	Caatinga Δ (×10^3 ha)	Pantanal Δ (×10^3 ha)	Atlantic Forest Δ (×10^3 ha)	Pampa Δ (×10^3 ha)
Cerrado/Amazon	17	53.2	17.6	433.2	98	-74.1	83.4	-35.2	-2.2
Cerrado/Atlantic Forest/Pampa	6	53.8	16.7	-1126.2	-373.3	-59.5	166.5	5.5	3.9
Cerrado/Caatinga	10	43.8	20	1763.6	316.9	226.6	-430.9	72.6	0.2
Cerrado/Pantanal	6	62.3	33.3	205.5	-298	5.5	205.4	9.8	3.8

Δ = mean (anthropogenic burned area – natural burned area) over all periods in each Attraction Region; positive values indicate relatively greater burned area in anthropogenic land use, negative values indicate relatively greater burned area in natural vegetation.

DISCUSSION

The spatial trajectories of Brazil's fire centroids provide a simplified but revealing lens through which to interpret four decades of interactions among climate variability, biome flammability, and human land use. The persistent separation between centroid positions for natural vegetation and anthropogenic use reflects fundamental differences in ignition patterns, fuel structure, and land-use history. Fires in natural savannas of the Cerrado, where fuel continuity and ecological flammability are intrinsic, remain concentrated within ecologically recurrent regions. In contrast, anthropogenic fires follow patterns of land conversion, pasture renewal, crop expansion, and deforestation, resulting in consistent westward and northwestward displacements aligned with the Arc of Deforestation. These contrasts align with biome-level differences in fire determinants outlined by Pivello (2021) and Oliveira et al. (2022), supporting the notion that natural and anthropogenic fire regimes occupy partially overlapping but structurally distinct spatial domains.

The polar histogram of centroid displacements confirms that centroid trajectories are far from random in directional space. Most interannual shifts fall within a limited set of directional sectors, and in most years, natural and anthropogenic centroids move in broadly similar directions: 'aligned' or 'moderately aligned' intervals dominate, whereas truly 'divergent' years are comparatively rare and directionally scattered. This pattern suggests that, despite their distinct spatial domains, the two fire regimes often respond to shared broad-scale gradients—such as the configuration of savanna–forest interfaces, the distribution of agricultural frontiers, and large-scale drought patterns—while maintaining different "centers of gravity" of fire activity. In other words, natural and anthropogenic fires tend to move in the same general direction, but they do so from and towards different parts of the landscape.

The striking convergence of natural and anthropogenic centroids in 2024 illustrates how extreme climatic anomalies can temporarily override these ecological distinctions. This convergence was driven by an unprecedented surge in natural-vegetation fires within the Amazon biome (Supplementary Table S1). MapBiomas data reveal a record-breaking increase of roughly 5 million ha in burned natural vegetation in the Amazon during the 2023–2024 period—about twice the variation observed in previous extreme years (e.g., ~2.5 million ha in 1986–1987). This massive anomaly shifted the "center of mass" of natural fires northwestward, aligning it with the anthropogenic footprint, which is typically concentrated along the Arc of Deforestation. Triggered by the 2023–2024 El Niño drought, this event demonstrates that extreme climatic synchrony can homogenize flammability thresholds, expanding the spatial domain of fire into regions that otherwise respond idiosyncratically to ignition pressures.

Directional movements also highlight the persistent role of anthropogenic dynamics. Years in which centroids shift towards the Cerrado–Amazonia sector align with periods of intense deforestation fires, including 1997–1998, the 2000s expansion of Mato Grosso agriculture, the 2019 "Dia do Fogo", and the 2023–2024 crisis. Shifts towards the Pantanal sector are similarly consistent with hydrological extremes and pasture burning in 2020–2021 (Pereira et al., 2025). These associations support the interpretation of centroid trajectories as diagnostic signals of underlying socio-ecological processes rather than as purely geometric abstractions.

Contrary to expectations for fire regimes strongly modulated by interannual climatic variability, the directional divergence between natural and anthropogenic centroid trajectories showed no consistent relationship with El Niño, La Niña, or ZCAS-related droughts. Even under a deliberately permissive classification, in which anomalies were assumed to influence both the year of occurrence and neighboring transition periods, statistical tests revealed no systematic link between climatic events and directional coherence. Climatic anomalies clearly modulate the extent of burned areas, but our results suggest that they do not impose a stable directional template on the redistribution of natural and anthropogenic fire activity across regions. Instead, the spatial reorganization of burned areas appears to respond to distinct structural drivers—ecological, socioeconomic, and landscape-related—that differ between natural vegetation and human-dominated land uses.

Our biome-level analysis provides only partial support for the hypothesis that directional divergence between natural and anthropogenic trajectories is tightly driven by changes in the redistribution of burned areas across biomes (H4). Multivariate models relating angular divergence or the probability of 'divergent' intervals to biome-level changes in burned area exhibited modest explanatory power, with no individual predictors being significant, indicating that no single biome or regime dominates the signal at the national scale. Nevertheless, summaries by Attraction Region (Table 1) reveal coherent spatial signatures. Intervals in which trajectories are attracted towards the Cerrado/Amazon sector tend to combine relatively stronger anthropogenic burning in Cerrado, Amazon, and Pantanal with a greater contribution of natural-vegetation fires in Caatinga and Atlantic Forest, whereas intervals attracted towards the Cerrado/Atlantic Forest/Pampa sector show broadly positive deltas in several eastern and southern biomes and reduced anthropogenic burning in the Pantanal. Attraction towards the Cerrado/Caatinga and Cerrado/Pantanal sectors is associated with more mixed patterns, in which natural and anthropogenic burning trade dominance across adjacent biomes. These patterns suggest that centroid trajectories integrate a complex, multi-biome mosaic of natural and anthropogenic fire rather than responding to simple shifts in a single biome, and that sub-biome heterogeneity in land use and fire management is likely to modulate centroid behavior in ways that coarse biome-level summaries cannot fully resolve.

Centroid trajectories intentionally simplify complex burned-area distributions and do not substitute pixel-level or patch-level analyses; however, they capture spatial reorganization at a scale that other metrics rarely address. Although centroid analysis cannot describe local heterogeneity or patch-scale fire behavior, its strength lies in detecting large-scale, directionally coherent trends that align with known climatic and land-use drivers. When integrated with biome-specific knowledge, the trajectories reveal a persistent pattern: fire activity in Brazil has undergone directional reorganization, with phases of attraction towards different biome interfaces corresponding to shifts in the interplay among drought, land use, vegetation flammability, and ignition pressure. This perspective helps frame recent crises—such as the widespread Amazonian burning of 2023–2024—within a broader historical context of spatial redistribution of fire and provides a compact diagnostic tool that can be updated as new burned-area and land-cover products become available.

METHODS

We combined open remote-sensing products with an open-science workflow documented in the Open Science Framework (OSF). The OSF project archives the preregistration, derived datasets, and all analysis code, providing a fully reproducible pipeline from patch-level burned areas to directional centroid trajectories.

Long-term spatial trajectories of fire activity were quantified using annual burned-area maps from MapBiomas Fire Collection 4 (1985–2024). Burned pixels were classified into two broad fire types: 'Natural Vegetation' and 'Anthropogenic Use' based on pixel-level spatial correspondence with the annual land use and land cover (LULC) maps from the MapBiomas Project. The Natural Vegetation regime aggregates all native classes (e.g., Forest Formation, Savanna Formation, Grassland, Wetland), while Anthropogenic Use encompasses all human-modified classes (e.g., Pasture, Agriculture, Forest Plantation, Mosaic of Uses). This binary classification follows the standard Level 1 hierarchy of the

MapBiomas legend. A complete list of the specific LULC classes aggregated into each regime is provided in Supplementary Table S2.

Burned patches were defined as contiguous clusters of burned pixels using rook (4-neighbour) connectivity applied to the annual burned-area maps. For each patch, we computed its geographic centroid (longitude and latitude) and area in hectares. To reduce the influence of very small, potentially noisy patches, we applied a minimum size threshold and retained only patches with at least four pixels (NumPixels ≥ 4), which correspond to approximately 0.36 ha at 30 m spatial resolution. All centroid and trajectory analyses are based on this filtered set of patches.

Coordinates were recorded in geographic space, and year-to-year displacement vectors were calculated using great-circle distances (haversine formula) and azimuthal direction in degrees. Centroid trajectories were evaluated using standard circular-statistics procedures, with all angles expressed in the 0–360° range.

Assessment of spatial separation between regimes

To formally evaluate whether fires in natural vegetation and anthropogenic areas form consistently distinct spatial clusters, we quantified separability using three complementary metrics:

1. Inter-centroid distance. For each year t, we computed the great-circle distance between the centroids of Natural Vegetation and Anthropogenic Use. The resulting time series (1985–2024) provides a direct measure of the annual spatial gap between regimes. We summarized this distribution using mean, variance, and minima to identify years of exceptional convergence.

2. Dunn Index for cluster separation. To compare inter-cluster separation to intra-cluster dispersion, we assembled all natural and anthropogenic centroids into a single dataset and computed (i) the minimum inter-cluster distance between points of different regimes and (ii) the maximum intra-cluster distance within each regime. The Dunn Index (DI) was then calculated as:

$$DI = \frac{\delta\left(C_i, C_j\right)}{\Delta\left(C_k\right)}$$

where $(\delta(C_i, C_j))$ is the smallest distance between points belonging to different clusters (C_i) and (C_j), and $(\Delta(C_k))$is the largest within-cluster distance for any cluster (C_k). Values close to zero indicate high internal dispersion relative to between-cluster separation, whereas higher values indicate well-defined, compact clusters.

3. Kernel Overlap Index (KOI). To estimate the degree of spatial interpenetration between the two distributions of centroids, we applied a bivariate Gaussian kernel density estimation (KDE) to both regimes. Spatial overlap was quantified as:

$$KOI = \int \quad \left(f_{nat}(x), f_{use}(x)\right) \; dx$$

where $(f_{\mathrm{nat}}(x))$ and $(f_{\mathrm{use}}(x))$ are the KDE surfaces for natural and anthropogenic centroids, respectively. KOI ranges from 0 (no overlap) to 1 (complete coincidence). This analysis captures the structural similarity between the spatial distributions, independent of temporal order. Taken together, these metrics characterise not only the distance between the "clouds" of centroids but also their relative dispersion and degree of overlap, providing a quantitative basis for assessing persistent spatial separation between natural and anthropogenic fire regimes.

Climate anomaly assignment

We associated each interannual centroid-shift interval ($t \rightarrow t+1$) with the occurrence of significant climate anomalies using publicly available classifications of ENSO (El Niño and La Niña) and South Atlantic Convergence Zone (SACZ/ZCAS)-related droughts (Atlantic-driven blocking events). Because these anomalies rarely align perfectly with calendar years and their ecological and fire-related impacts often extend beyond their peak phase, we adopted a permissive assignment rule: if year t+1 was classified as El Niño, La Niña, or SACZ-active, then the adjacent intervals ($t \rightarrow t+1$ and $t+1 \rightarrow t+2$) were also considered under the influence of the same anomaly. This approach reduces false negatives (i.e., intervals incorrectly treated as unaffected) and is conservative in assessing the potential climatic influence on directional divergence.

Classification of directional alignment

The angular difference between natural and anthropogenic displacement vectors was calculated as the minimal circular difference between the two interannual directional angles (0–180°). To categorize the degree of directional similarity, we used three alignment classes: 'aligned' (<45°), 'moderate' (45–90°), and 'divergent' (>90°). This threshold-based classification provides an interpretable measure of relative alignment that is independent of geographic orientation.

Directional summaries and polar histogram

To summarize the directional structure of centroid trajectories, we used the bearings of the natural-vegetation displacement vectors between consecutive years as a reference. For each interannual interval, the displacement angle of the natural centroid was mapped to the 0–360° range (0° = north, increasing clockwise), and intervals were assigned to one of twelve 30° directional sectors. Each interval was also classified into one of three alignment classes according to the absolute angular difference between natural and anthropogenic displacement vectors: 'aligned' (<45°), 'moderate' (45–90°), or 'divergent' (>90°) (see above). We then constructed a stacked polar histogram in which bars represent the number of intervals in each directional sector, partitioned by alignment class. The figure thus shows both the dominant directions of centroid shifts and the relative frequency of aligned, moderately aligned, and divergent movements between the two fire regimes. Colors were chosen from a color-blind-safe palette (Okabe–Ito) to maximize interpretability.

Biome-level burned area and Attraction Regions

To examine whether directional divergence between natural and anthropogenic trajectories reflects underlying changes in the spatial distribution of burned area across biomes (H4), we computed annual burned area in natural vegetation and anthropogenic land use for each Brazilian biome (Cerrado, Amazon, Caatinga, Pantanal, Atlantic Forest, and Pampa). For each interannual interval, we derived biome-level deltas as the difference between anthropogenic and natural burned area (Δ = use – natural), so that positive values indicate relatively greater burned area in anthropogenic land use and negative values indicate dominance of natural-vegetation burning. We then grouped intervals according to the sector towards which the centroid trajectories were oriented, defining four Attraction Regions (Cerrado/Amazon, Cerrado/Caatinga, Cerrado/Atlantic Forest/Pampa, and Cerrado/Pantanal) based on the compass bearing of the displacement vectors. For each Attraction Region, we summarized:

(i) the mean angular difference between natural and anthropogenic trajectories,
(ii) the proportion of Divergent intervals, and
(iii) mean biome-level deltas. As an exploratory check, we also fitted multivariate linear models relating angular difference to biome-level burned-area changes, and logistic models relating the probability of Divergent intervals to biome-level deltas. Given the modest explanatory power and lack of statistically significant coefficients, these models are interpreted descriptively rather than as formal confirmatory tests.

Statistical evaluation of climate influence

To investigate whether directional divergence is associated with climate anomalies, we employed three complementary statistical procedures.

(i) Angular differences among climate categories. We compared angular differences among climate categories (El Niño, La Niña, SACZ, Mixed, and None) using the non-parametric Kruskal–Wallis test, as the angular differences were not normally distributed.
(ii) Contingency between climate categories and alignment classes. We evaluated whether the frequencies of alignment classes differed across climate categories using a chi-square test for contingency.
(iii) Logistic regression for divergent intervals. Finally, we fitted a logistic regression model with *Divergent* (yes/no) as the response and El Niño, La Niña, and SACZ indicators as predictors, optionally including a centred time term. Complete separation prevented model convergence, indicating the absence of a robust learnable association between these climate indicators and strongly divergent trajectories. All analyses were performed in Python using the packages 'pandas', 'SciPy', and 'statsmodels'.

Preregistration

This study was retrospectively preregistered in the Open Science Framework (OSF) under the title Directional centroid trajectories of burned areas in Brazil (OSF registration: 10.17605/OSF.IO/WA326). The preregistration describes our main hypotheses, data sources, and planned statistical models. The analyses reported here follow that plan with minor clarifications, including the explicit minimum patch-size filter. Any deviations from the original plan are documented in the OSF record.

Data availability

All derived datasets used in this study are openly available in an OSF project (OSF: 10.17605/OSF.IO/WA326). The repository includes:

(i) annual centroid positions and summary statistics for burned natural vegetation and anthropogenic land use (centroids_annual.csv);

(ii) patch-level burned-area datasets for each year and group, provided via a linked Google Drive folder (patches_fire_{year}_filtered.csv); and
(iii) tables linking angular differences between trajectories to climate events and biome-level burned areas (direction_diff_with_climate_events.csv, variation_burned_area_biomes.csv).

Original land-use/land-cover and burned-area maps were obtained from the MapBiomas project and can be accessed through their platform; we provide direct links and citations in the OSF documentation.

Code availability

All scripts used to process patch-level burned areas, compute annual centroids, derive trajectory metrics, and perform the statistical analyses are available in the same OSF project under the 03_Code folder. The code is organized by workflow step (patch extraction, centroid calculation, trajectory statistics, and figure generation) and is sufficient to reproduce all results reported in this manuscript from the derived datasets.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author utilized Grammarly to enhance readability and language, as well as large language model tools (such as ChatGPT and Gemini) to assist in generating Python code for data processing and refining the manuscript's wording. After using these tools, the author reviewed and edited all content as needed and takes full responsibility for the final version of the text and analyses.

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