Unravelling Global Fire Regimes: Seasonal Mapping and Multi-Variable Characterization of Fire Activity

Athira V. Mukundan, Arijit Roy*, Ajay Kumar, Harish Chandra Karnatak

Indian Institute of Remote Sensing, Indian Space Research Organisation (ISRO), Dehradun, India

athiraiirs@gmail.com, arijitroyiirs@gov.in*, ajayiirsphd@gmail.com, harish@iirs.gov.in

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Abstract

Wildfires are fundamental ecological processes that shape terrestrial ecosystems and influence atmospheric dynamics. This study presents a global assessment of fire frequency, intensity, and burned extent over a 24-year period (2001-2024) using multi-source satellite observations. Spatio-temporal variability of forest fire activity and the critical role of seasonality in modulating fire behaviour has been captured in a grid of 0.25°. Our results reveal clear regional and hemispheric patterns wherein southern and central Africa, northern Australia, and parts of South America consistently exhibit the highest fire activity, with strong spatial and seasonal variability. In contrast, the Northern Hemisphere remains relatively stable, with lower fire occurrence and limited changes over time, aside from modest seasonal fluctuations in certain regions. Seasonal dynamics are especially pronounced in the tropics, reflecting variations in climatic drivers and fuel availability. To explore interactions among fire parameters, we conduct grid-level correlation analyses, revealing strong positive associations among frequency, intensity, and extent in tropical and subtropical regions. These relationships weaken or decouple in temperate and boreal zones, highlighting the influence of seasonal climate and vegetation dynamics. Building on these insights, clustering-based classification was used to delineate global fire regimes based on the combined behavior of the three parameters. The resulting maps reveal distinct spatial configurations and temporal evolution, with dynamic regime shifts across much of the Southern Hemisphere and comparatively stable regimes in the north.

1. Introduction

Fire is an essential ecological force that shapes terrestrial ecosystems in multiple ways. It alters vegetation structure, influences species composition, and plays a role in carbon flow between the land and the atmosphere (Harris et al., 2016; Bowman et al., 2009). The spatial and temporal patterns of fire activity, collectively referred to as fire regimes, are characterized by multiple parameters, including frequency, intensity, extent, seasonality, and severity (Agee, 1993). The way vegetation characteristics, climate, and land use interact shapes these patterns, often producing feedbacks that vary by biome and region (Pausas & Keeley, 2009). In recent decades, fire regimes have begun to shift markedly under the influence of anthropogenic climate change, which is altering both the physical conditions that enable fire and the ecological responses that follow. Tropical ecosystems, particularly savannas, have always been subject to frequent, low-intensity fires, largely caused by the availability of continuous fuel and distinct seasonal dryness (Brando et al., 2014). On the other hand, fire regimes in boreal and temperate forests are typically characterized by less frequent but more intense fires, often triggered by prolonged droughts and extreme heat events (Williams & Abatzoglou, 2016). In addition, fire dynamics is also influenced by human activities, including land-use changes, fire suppression efforts, and the deliberate use of fire, especially along the agricultural-forest margins (Andela et al., 2017).

Global satellite records show that total burned area is following a declining trend since the early 2000s, likely causes being agricultural expansion and better fire control (Brando et al., 2014; Keeley and Zedler, 2009). However, such global patterns can mask important regional and seasonal changes in other fire-related characteristics. In many places, fire intensity is rising, fire seasons are becoming longer. Fire behaviour is also more unpredictable, even when the burned area is getting reduced (Flannigan et al., 2009). These shifts suggest that burned area alone is not enough to understand fire regimes. This study responds to that gap, by presenting a global analysis of fire regimes from 2001 to 2024, using MODIS satellite data with seasonal analysis. For this study, we examined fire frequency, fire intensity using Fire Radiative Power (FRP), and burned extent. These three factors help us classify fire regimes across space and time. Our approach provides new insight into changing fire patterns. It also highlights how these changes may affect ecosystem processes, climate feedback and land management.

2. Materials and Methods

2.1 Study Area and Analytical Framework

This study was carried out at the global level. It focused only on vegetated land areas where wildfires are a regular part of the ecosystem. The analysis covered forests, shrublands, and grasslands as these biomes have long been linked to high fire activity. The land surface was divided 0.25 degree gridded framework for the study. This uniform grid helped maintain spatial consistency and allowed comparisons across different ecological zones. This design was used to capture how fire behaviour changes across space. It reflects scales that are important for understanding ecosystems and for supporting fire management.

2.2 Data Sources and Pre-processing

The study used MODIS satellite products from January 2001 to December 2024. Active fire data were taken from the NASA FIRMS archive using the MCD14ML product. Fire frequency was calculated as the number of active fire detections per grid cell for each month. Fire intensity was based on the Fire Radiative Power (FRP) linked to these detections. Burned area extent was estimated using the MCD64A1 product, which maps fire-affected areas at 500 meter resolution. These data were then aggregated to find the monthly proportion of each grid cell that burned. To keep the datasets aligned, all data were resampled to a 0.25 degree grid. The study period was divided into four six year periods: 2001 to 2006, 2007 to 2012, 2013 to 2018, and 2019 to 2024. For each period, we calculated the total fire frequency, average FRP, and mean burned area for each calendar month. This resulted in 36 values per grid cell for every period. That includes 12 months for each of the 3 parameters. This method preserved seasonal patterns and allowed comparisons of fire regime dynamics over time.

Parameter	Dataset/Product	Spatial Resolution
Fire Frequency (FF)	MODIS Active Fire (MCD14ML)	1 km
Fire Intensity (FI)	MODIS FRP from MCD14ML	1 km
Burned Extent (BE)	MODIS Burned Area (MCD64A1)	500 m
Land Cover Mask	ESA CCI Land Cover	300 m
Fire Seasonality	Derived from MODIS Active Fire	1 km

Table 1: Datasets used for deriving global fire regime parameters

2.3 Fire Regime Classification

To characterize global fire regimes, the study employed two complementary approaches: a rule-based typology derived from absolute parameter values and an unsupervised clustering of seasonal patterns. The rule-based classification was based on three core fire parameters, frequency, intensity, and extent, calculated for each of the four time intervals. For each parameter, global median values were computed, and grid cells were categorized as either "high" or "low" relative to these thresholds. This binary classification across three dimensions produced eight distinct fire regime types (e.g., High Frequency-High Intensity-Low Extent [HHL], Low Frequency-Low Intensity-High Extent [LLH]), providing a compact yet informative framework to summarize dominant fire behaviours and facilitate temporal and spatial comparisons.

To complement this typology and capture intra-annual variability, a seasonal clustering analysis was performed. For each grid cell and time interval, the twelve-month values of fire frequency, intensity, and extent were combined into a 36-variable descriptor. These time series were standardized and subjected to k-means clustering using the Euclidean distance metric. Rather than relying on statistical indices, the number of clusters was selected based on interpretability and the ability to reflect meaningful distinctions in seasonal fire dynamics. Each cluster thus represents a unique fire regime defined by its recurring monthly pattern, offering insights into the temporal structure of fire activity that annual averages may obscure.

3. Results

3.1 Spatial and Temporal Patterns of Fire Frequency, Intensity, and Burned Extent

Global fire activity exhibits distinct spatial patterns across all three core fire regime variables, frequency, intensity, and extent, over the 2001-2024 period. Fire frequency is consistently highest across the tropical belt, particularly in southern and central Africa, northern Australia, the Amazon Basin, and Southeast Asia. These regions are characterized by abundant biomass and strong seasonality, conditions that support frequent ignitions and sustained surface fires. Fire intensity, represented by mean Fire Radiative Power (FRP), generally aligns with fire frequency hotspots but also reveals episodic high-intensity fire activity in the boreal forests of Siberia and Canada. These boreal systems, despite experiencing less frequent fire events, exhibit extreme intensities during drought years, suggesting that fuel accumulation and climate anomalies act as amplifiers of fire severity. Burned extent follows a similar geographic distribution, with the African continent accounting for the largest continuous burned area globally. Extensive savanna fires dominate this signal, yet substantial burned area is also observed in Australia's interior ecosystems, underscoring the global diversity of fire-prone environments. Temporal trends reveal a modest yet consistent global decline in total burned area over the study period, supporting earlier findings (Andela et al., 2017). However, this decline is not mirrored by fire frequency or intensity. In several regions, particularly the boreal and subtropical zones, fire events have become more intense or more frequent despite a net reduction in area burned. This divergence suggests a transition toward more episodic, severe fire regime, potentially influenced by climate extremes and human suppression efforts that modify fuel continuity and ignition patterns.

3.2 Seasonal Dynamics and Hemispheric Contrasts

Fire activity exhibits strong seasonal signatures that vary distinctly between hemispheres and biomes. In the Southern Hemisphere, particularly in sub-Saharan Africa, northern Australia, and South America, fire peaks during the dry season, typically austral winter and spring. These peaks coincide with low precipitation and high evapotranspiration, leading to widespread ignition and fire propagation. In contrast, the boreal forests of the Northern Hemisphere exhibit concentrated fire activity during the summer months. However, this pattern is highly variable across years, reflecting the sensitivity of these systems to interannual climate variability, especially drought and heatwave events (Kelly et al., 2013). Boreal fires, though less frequent, are often high in intensity and have disproportionately large ecological impacts due to deep burning and long recovery times. Temperate regions, including parts of Europe, eastern Asia, and the eastern United States, display less distinct seasonality. In these zones, fire regimes are shaped by land management practices, prescribed burning, and agricultural cycles, resulting in year-round, low-frequency fire activity. These anthropogenic influences effectively blur the climatic signals typically seen in natural fire systems.

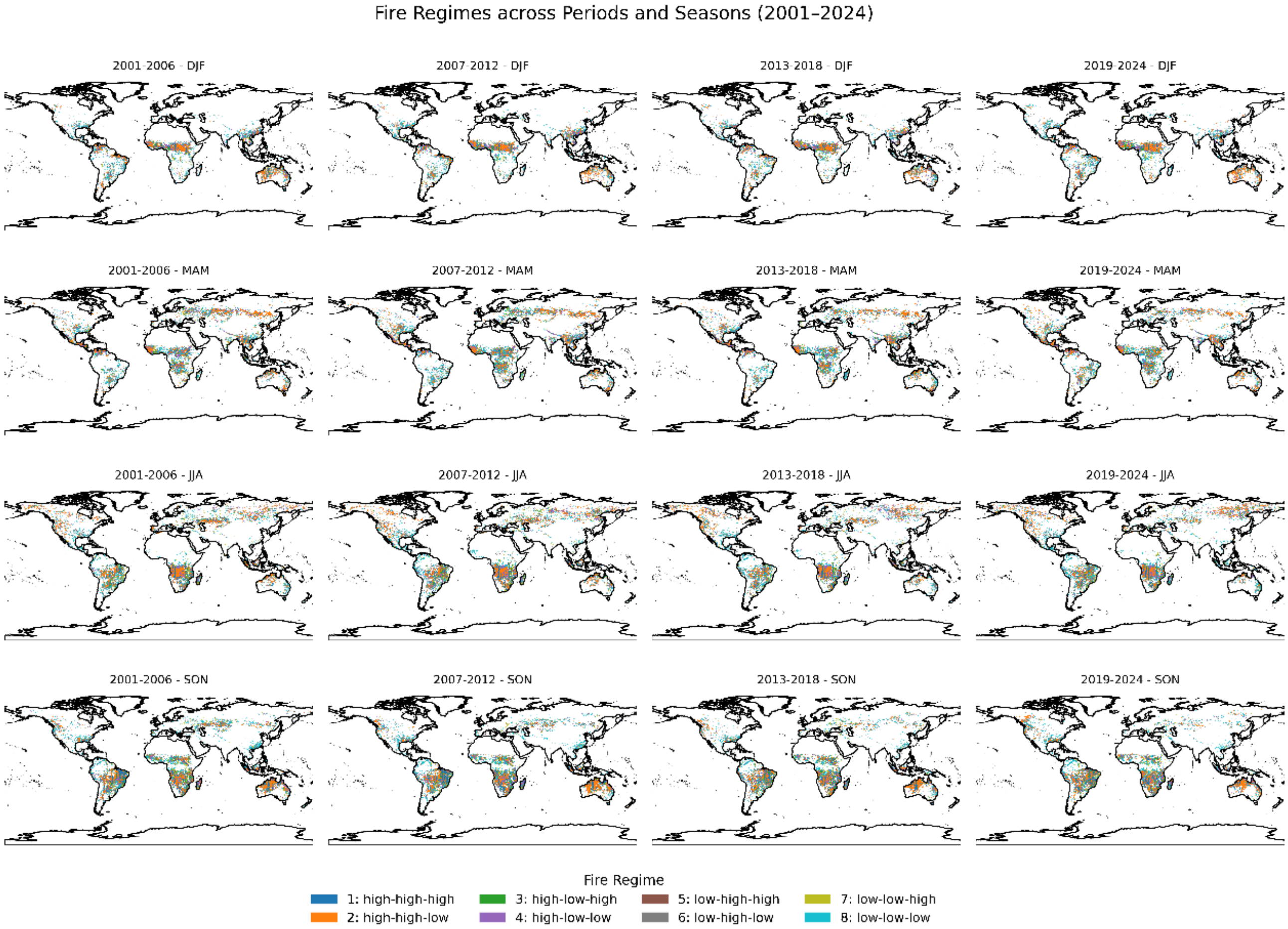

Figure 1: Spatiotemporal characterization of global fire regimes

3.3 Fire Regime Classification Based on Combined Attributes

To synthesize the complexity of global fire behaviour, we classified each grid cell into one of eight fire regimes, based on three core parameters: fire frequency, intensity, and extent. For each parameter, median thresholds were used to separate high (H) and low (L) values, resulting in eight possible combinations: HHH, HHL, HLH, HLL, LHH, LHL, LLH, and LLL. The HHH regime, characterized by high values across all three parameters, dominates the savannas of central and southern Africa and northern Australia, reflecting frequent, intense, and spatially extensive fires. Regimes such as HHL or HLH appear in transitional ecosystems like the South American Cerrado or the boreal margins, where one or more fire characteristics are elevated but not all. Low-fire regimes (LLL, LHL) are prevalent in heavily managed or fragmented landscapes, including much of Europe, India, China, and the eastern United States. Temporal analysis shows a gradual decline in high-extent regimes (especially HHH and HLH) over the 24-year period. Conversely, there is an increase in regimes where intensity remains high but burned extent is low (e.g., LHL and LLH), particularly in subtropical and boreal regions. These shifts suggest a transition toward shorter-duration, higher-energy fires possibly associated with changing fuel structures and climatic extremes. Regions undergoing regime transitions most frequently include southern Africa, northern Australia, and the Amazon basin, underscoring their sensitivity to both climatic variability and land-use changes. While global classifications provide a useful broad picture of fire regime patterns and their temporal changes, they often obscure important regional differences shaped by local climate, vegetation, and human activity. To uncover these spatial nuances, we conducted separate analyses for fire-prone regions like South America, Africa, and Australia. This continental-scale approach allowed for a more refined understanding of how fire behaviour is shaped by regional ecological and socio-environmental drivers that may be masked in global assessments.

South America

Fire regimes across South America reflect the continent's ecological diversity and the growing influence of land use. The Cerrado and adjacent savanna regions stand out with consistently high fire activity, particularly during the dry season, where fires play a well-established role in maintaining open vegetation, recycling nutrients, and supporting fire-adapted species. In contrast, the Amazon rainforest and Andean zones are generally

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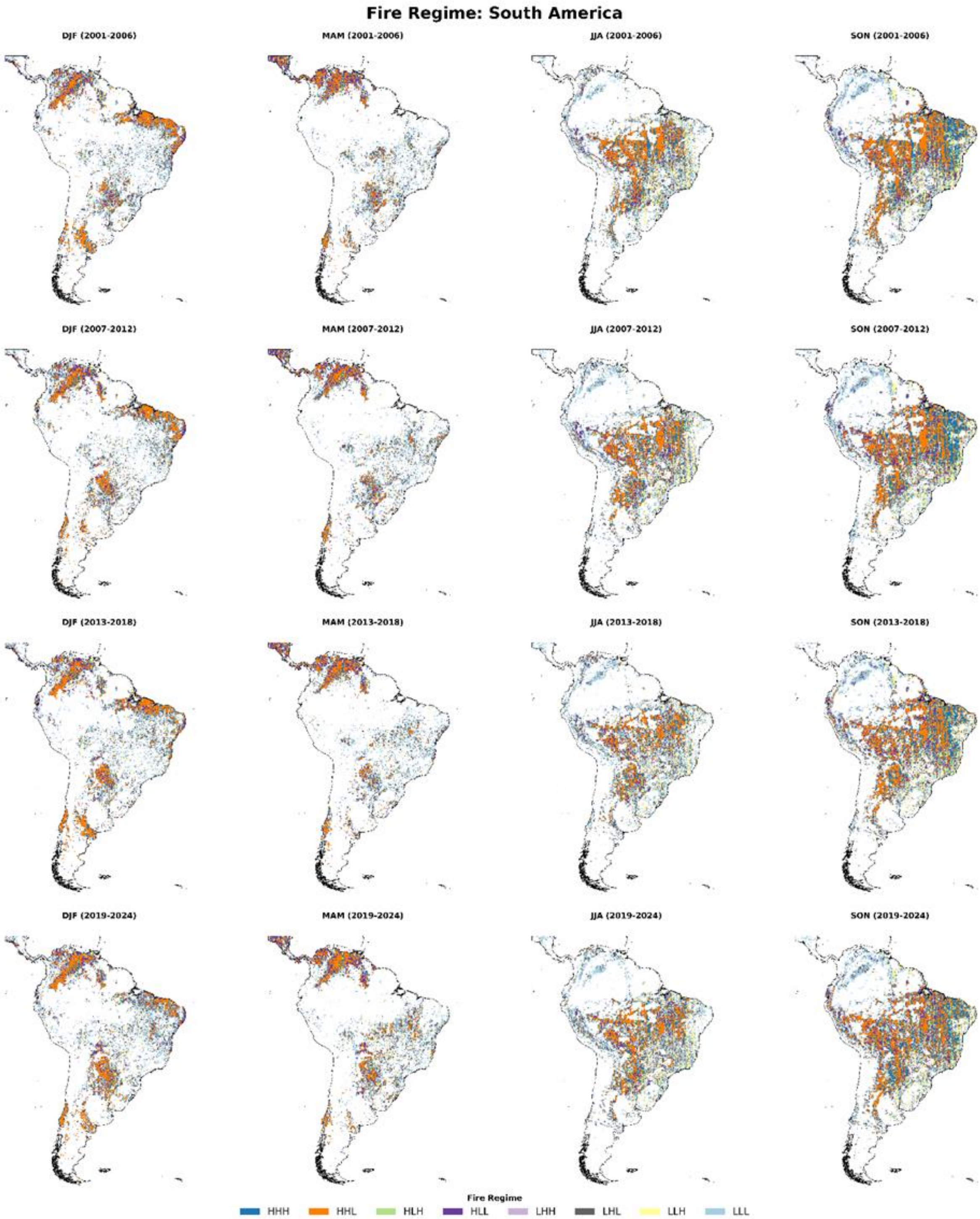

Figure 2: Spatiotemporal characterization of fire regimes of South America

characterized by lower fire activity, though this pattern is not uniform. In contrast, the Amazon rainforest and Andean zones are generally characterized by lower fire activity, though this pattern is not uniform. In recent years, noticeable fire activity has emerged in the northern Amazon during DJF and MAM, periods typically associated with wetter conditions. This likely points to land-use-related burning, such as deforestation, pasture clearing, or edge fires, rather than natural ignitions. These observations underscore the interplay between ecological context, seasonal climate, and human influence in shaping fire regimes across the region.

Africa

Fire regimes across Africa display clear seasonal shifts and strong geographic consistency over time. High-fire regimes (especially HHH and HHL) dominate much of the continent's savanna and woodland regions, with patterns that follow the progression of the dry season. Fire activity peaks in the northern savannas during the DJF and MAM seasons, while JJA and SON experience a southward shift in fire intensity and extent, particularly across Angola, Zambia, and surrounding areas. These fires play an important ecological role in maintaining open

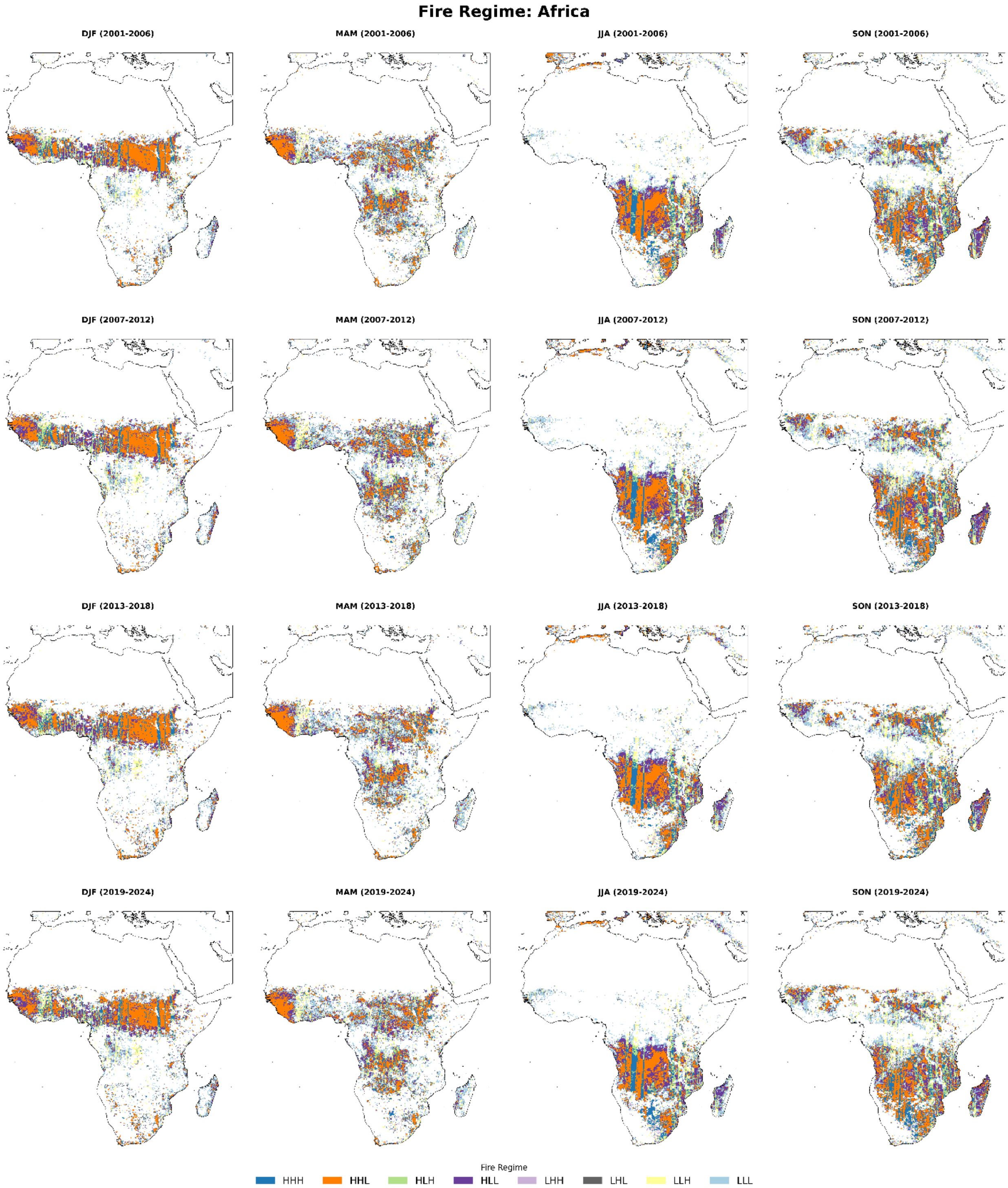

Figure 3: Spatiotemporal characterization of fire regimes of Africa

landscapes and supporting fire-adapted vegetation. In contrast, lower fire activity is observed in more arid northern regions and wetter zones where fuel or ignition limitations restrict fire spread. Although the overall spatial extent of high-fire regimes has remained relatively stable, some localized changes are evident, potentially linked to shifts in land use or fire management practices.

Australia

Fire activity in Australia shows strong regional variation, shaped by the continent's climate and vegetation. These areas consistently fall into HHH and HHL regimes, reflecting the well-established role of fire in maintaining tropical savannas. Further south, patterns are less consistent. The arid interior is mostly dominated by low-fire regimes due to limited fuel availability, while temperate regions in the southeast show more variation

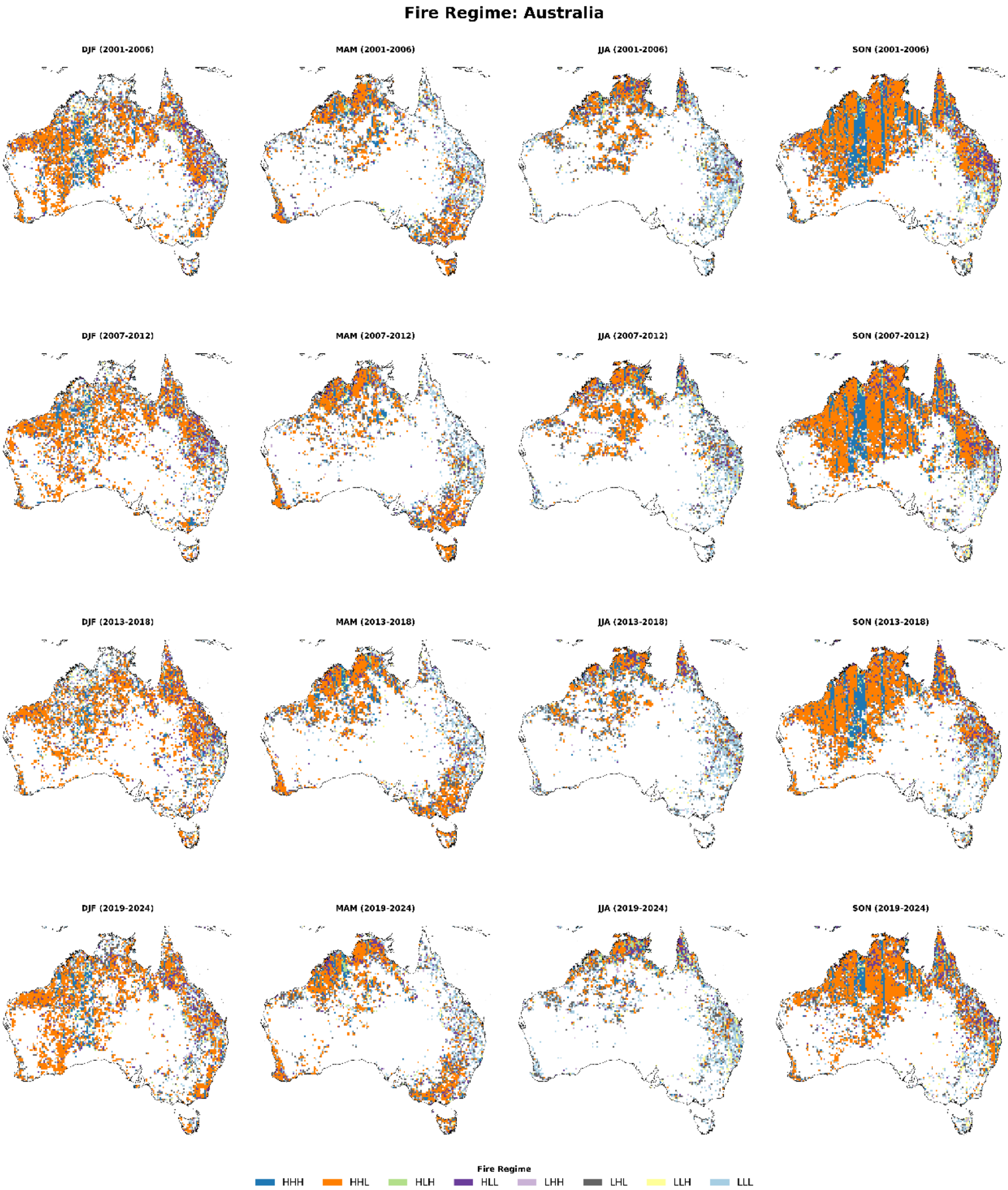

Figure 4: Spatiotemporal characterization of fire regimes of Australia

across seasons and years. Some increases in fire activity are visible in certain periods, but they remain patchy and far less extensive than in the north. Overall, fire regimes across Australia are closely tied to seasonal climate, but local conditions and land use introduce important spatial differences in how fire behaves.

4. Discussion

4.1 Ecological Insights and Management Implications

This study advances global fire ecology by refining our understanding of how fire regimes vary across space and seasons over the past two decades. Using MODIS data, we classified fire regimes based on frequency, intensity, and burned extent, and found that many systems continue to show strong seasonal patterns shaped by rainfall and fuel availability. This is especially true for savannas and tropical grasslands, where fire dynamics remain closely linked to climatic conditions, consistent with earlier work (Archibald et al., 2013; Mondal & Sukumar, 2016).

In several regions, we find that fire frequency, intensity, and extent tend to move together, pointing to the persistence of fuel-limited regimes. This supports previous findings that climate remains a key control on fire behaviour in many ecosystems (Hartung et al., 2021). However, our results also point to areas where this relationship is breaking down. In South America, for instance, fire activity in the Cerrado remains high, while dry-season burning is increasing in parts of the Amazon, a trend also reported by da Silva Arruda et al. (2024). In Africa, high-frequency fire regimes still dominate the savanna belt, but we observe early signs of change near its ecological edges, which aligns with regional shifts noted by Archibald et al. (2012) and Laris (2021). Northern Australia continues to show seasonally driven fire activity, but southeastern parts of the continent display more variable fire behaviour in recent years. Our findings reflect this contrast, with relatively stable regimes in the north and more mixed patterns in the south and east, similar to the trends described by Wurster et al. (2021).

Overall, we see evidence of emerging fire regime shifts in several parts of the world. These appear to be driven not only by climate variability but also by human impacts, including deforestation, land use change, and altered fire management (Sayedi et al., 2024; Loudermilk et al., 2022). In some places, these changes are making fires more frequent or more intense, even as the total area burned globally is declining. This matches broader patterns observed in earlier studies (Andela et al., 2017; Brando et al., 2014). These shifts raise concerns about long-term ecological impacts. As fires become more intense or occur outside their historical timing, the risks to biodiversity, carbon storage, and human health increase. Our classification highlights where such changes are already underway and where more flexible, ecosystem-based fire management may be needed (Oliveras et al., 2025). By combining multiple fire parameters and including seasonality, this approach offers a more detailed view of global fire dynamics than regime maps based only on annual fire counts or burned area.

4.2 Methodological Considerations and Advances

While MODIS products offer unparalleled global coverage, limitations in spatial resolution and detection algorithms can lead to underestimation of low-intensity or understory fires, particularly under closed canopies (Chuvieco et al., 2019). Thus, fire extent and intensity estimates in tropical forests should be interpreted with caution. The use of k-means clustering enabled detection of seasonal patterns and regime transitions, but also introduces subjectivity in selecting cluster numbers and initialization conditions. Alternative unsupervised methods, such as hierarchical or model-based clustering, need exploration. Despite these uncertainties, our classification of fire regimes into eight median-based typologies presents a robust framework for characterizing fire behaviour. This extends previous assessments (Andela et al., 2017; Van Der Werf et al., 2017) by integrating seasonal variability and long-term trends, offering a more dynamic perspective on pyromes as originally conceptualized by Archibald et al. (2013). Such refined classifications are critical for anticipating future fire behaviour under accelerating environmental and socio-economic change.

5. Conclusions

This study offers a globally consistent, seasonally explicit classification of fire regimes over 24 years (2001–2024) using MODIS-derived observations of fire frequency, intensity, and burned extent. By integrating these parameters in a multi-dimensional framework and applying median-based thresholding, we delineate eight distinct fire regime types that reflect meaningful combinations of fire behaviour and landscape response. Our classification captures both stable fire-prone systems and regions undergoing rapid regime shifts. The results underscore the dominant influence of seasonality in regulating fire dynamics across latitudes, while also highlighting the growing impact of anthropogenic drivers, including land-use change and fire management practices. Regional increases in fire frequency and intensity, despite declining global burned area, reveal emerging hotspots of fire activity with potential consequences for carbon cycling, biodiversity, and human health.

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