The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLVIII-M-5-2024
ASPRS 2024 Annual Conference at Geo Week, 11–13 February 2024, Denver, Colorado, USA and 21–24 October 2024 (virtual)

Mapping Forest Fire Dynamics: A Global Perspective on Trends of Severity and Frequency Across Sub-Biomes

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Keywords: Forest fire dynamics; Sub-biomes; Active fire data; Mann-Kendall trend; Fire severity & frequency; Global fire hotspots

Abstract

Understanding forest fire dynamics at a global scale is crucial for effective management & mitigation strategies. This study presents a comprehensive analysis of forest fire trends for severity & frequency across sub-biomes globally, utilizing daily MODIS active fire data (2001-2023). The analysis integrates Mann-Kendall trend tests, Sen's slope estimations, & spatial mapping to elucidate the patterns of forest fire occurrences & their implications for different ecosystems. The Mann-Kendall trend analysis identified significant trends in fire severity across sub-biomes. Notable increasing trends were observed in the Tundras of tropical mountains in cryoro belt (1c), Lowland boreal Taiga (2a), Forests & shrublands of temperate oro belt (2b), & Forest-steppe (6a). Conversely, decreasing trends were detected in Tropical pluviseasonal forests & woodlands (8b) & Tropical rainforests (9a). Additionally, spatial assessment of forest fire frequency for the year 2023 provides a detailed visual representation of recent forest fire hotspots across the globe, highlighting regions with the highest fire frequencies. Notable hotspots include Tropical rainforests (9a), Tropical xeric shrublands & woodlands (8a), & parts of the African & South American continents, where fire activity was particularly intense. These regions, marked by high fire density, underscore the urgent need for targeted fire management strategies to mitigate impact of recurrent fires. The combined analysis of trends for severity, & frequency of forest fires offers valuable insights into the evolving fire regimes across global sub-biomes. The findings highlight the impacts of forest fires on biodiversity, carbon cycling, and ecosystem services, guiding more resilient strategies for global environmental changes.

1. INTRODUCTION

Forest fires are an important component in many terrestrial ecosystems playing a key role in structuring vegetation dynamics, driving nutrient cycling, and promoting biodiversity (He et. al., 2019). Historically, forest fires have played a crucial role in shaping landscapes, controlling species composition, and recycling nutrients. However, recent decades have seen an alarming rise in frequency, intensity, and the extent of these fires (Harvey, 2016; Singh, 2022). Forest fires are becoming more frequent in many regions due to changes in climate, human activities, and natural cycles. Among the changed global weather conditions, increased global temperatures, persistence droughts, and anthropogenic activities such as deforestation across the world have amplified the severity of fire regimes (Johnstone et. al., 2016). Understanding these shifts in fire dynamics is vital in formulating strategies for mitigating negative impacts on ecosystems, human life, and global climate patterns (Mamgain et. al., 2023).

Globally, different biomes and sub-biomes are impacted by forest fires in varied ways. The relationship between forest fires and climate change is particularly critical (Trumbore et. al., 2015). Global warming has led to more extended periods of drought, which reduces fuel moisture and makes forests susceptible to ignition (Harvey, 2016). For instance, these changes in the boreal and temperate zones have extended longer fire seasons and larger, more destructive fires. Simultaneously, tropical forests, which were previously resilient to fires due to high humidity and dense vegetation, are now at greater risk as deforestation and changing precipitation patterns make them more vulnerable to frequent burning (He et. al., 2019). These changes not only affect the forests themselves but also have far-reaching consequences for biodiversity, carbon sequestration, and the global carbon cycle.

The spatial and temporal dynamics of forest fires across different ecosystems form an integral part of effective management. The release of greenhouse gases such as carbon dioxide and methane in massive quantities due to forest fires has a multiplier effect in aggravating the situations of climate change and sets up a feedback loop that intensifies fire conditions (Arshad et. al., 2024). This phenomenon is termed as the fire-climate feedback loop and thus calls for thorough global assessments of trends and patterns in fire (Hoffmann et. al., 2002, Harris et. al., 2016). Particularly, due to their peculiar vegetation structure, climatic conditions, and fire history, biomes and sub-biomes respond to forest fires in very different ways (Moritz et. al., 2012). For example, while there is an increasing severity in fire in boreal forests because of the melting of permafrost and longer dry seasons, prominent human impacts and changing climate patterns rather threaten a more historic avoidance of being burned in the tropical rainforests (Corning et. al., 2024)).

This study aims to provide a global perspective on forest fire dynamics, focusing on the trends of severity and frequency across various sub-biomes from 2001 to 2023. Daily active MODIS fire data have been integrated with statistical methods, specifically Mann-Kendall trend test and Sen's slope estimation, for the analysis of changes in regimes of forest fires. Additionally, the study produces a Forest Fire Occurrence Density Map for 2023, highlighting recent hotspots and offering insights into which regions are most at risk. The results will provide key policy guidelines for policymakers, conservationists, and fire management authorities in developing adaptive strategies against the increasing threats of forest fires in a rapidly changing world.

This is to understand fire patterns in forests and the dynamic nature of such patterns in ecosystems around the world, an imperative in an age where climate change continues to grow in intensity and human interference more profound. It is an essential variable on which both natural and human environments are becoming increasingly reliant in protecting them from increasingly destructive regimes.

2. STUDY AREA

The study area covers the whole globe with a particular focus on diverse sub-biomes that represent a variety of ecological zones (Figure 1). These global sub-biomes (Loidi et. al., 2023) span the unique climatic and ecological conditions, range from the Polar tundra (1a), Tundras of the temperate mountains in the cryoro belt (1b), and Tundras of the tropical mountains in the cryoro belt (1c), which dominate the northern latitudes, to the Lowland Boreal Taiga (2a) in regions like Canada and Russia. The temperate regions are characterized by Forests and shrublands of the temperate oro belt (2b), Temperate deciduous forests (3a), Lauroid evergreen forests of the lowlands (4a), and Conifer coastal forests (4b), with these biomes stretching across parts of North America, Europe, and East Asia. The Tropical montane cloud lauroid and conifer evergreen forest (4c) is found in more humid mountainous regions.

In Mediterranean climates, Oceanic sclerophyllous-microphyllous evergreen forests and shrublands (5a) are found, while the Continental scrub and woodlands (5b) and Patagonian shrubland (5c) span dry inland areas, such as parts of South America and southern Africa. Grassland-dominated regions include the Forest-steppe (6a) and Grass-steppe (6b), which are prevalent across parts of Central Asia and North America (Loidi et. al., 2022). Desert areas, such as the Cold deserts and semi-deserts (7a) in Asia and the Warm deserts and semi-deserts (7b) in North Africa and Australia, experience infrequent fire activity, though certain climate shifts can alter fire regimes.

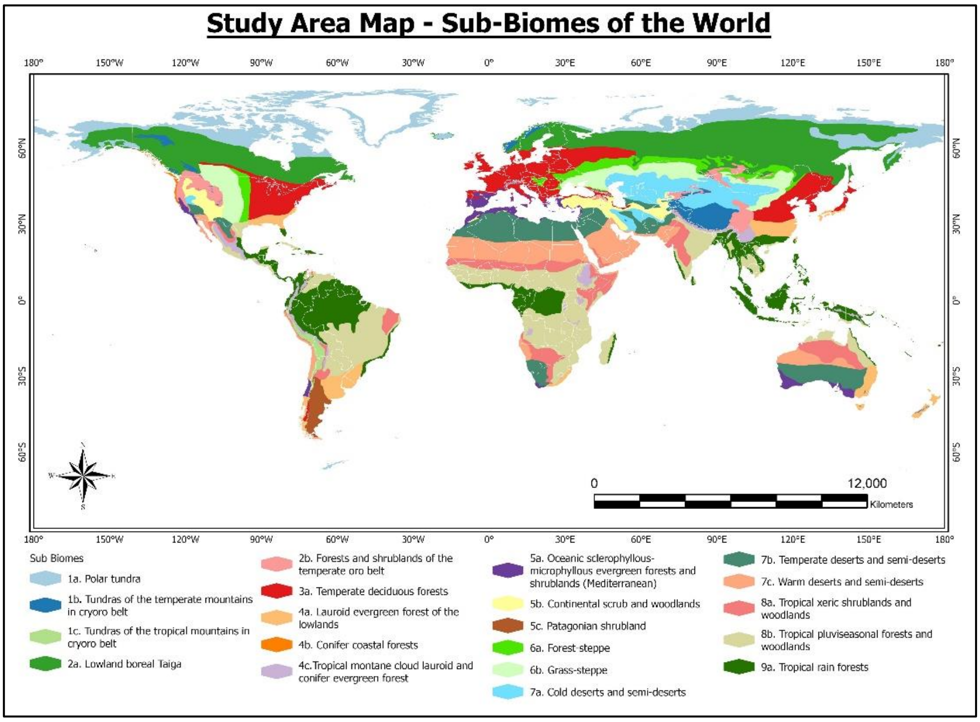

Figure 1. Study area map- Sub-biomes of the world (Loidi et. al., 2023)

The tropical regions, which are critical fire zones, include the Tropical xeric shrublands and woodlands (8a) in Africa and Australia, and the Tropical pluviseasonal forests and woodlands (8b) and Tropical rain forests (9a) in South America and Southeast Asia (Loidi et. al., 2022). These tropical sub-biomes are highly susceptible to forest fires, with the xeric shrublands being particularly prone to frequent fire outbreaks due to the dry conditions and anthropogenic pressures like deforestation and land-use changes. This comprehensive representation of sub-biomes highlights the diversity of ecosystems impacted by forest fires globally, with notable fire-prone regions in the boreal, temperate, and tropical zones. Understanding the dynamics of forest fires across these various sub-biomes is essential for global fire management and mitigation strategies. These sub-biomes provide a diverse set of ecosystems for studying the variability of forest fire dynamics across different environmental and climatic conditions.

3. MATERIAL AND METHOD

3.1 Satellite dataset

This study uses daily active fire data from the MODIS on board NASA's Terra and Aqua satellites. MODIS data provides the global daily fire detections at a spatial resolution of 1 km. MODIS data enables the monitoring of the fire activity in near-real time and captures the location of active fires, their Fire Radiative Power (FRP), levels of confidence in their detection, and the time fire was detected to be active. The dataset covers the period between 2001 and 2023, therefore providing a reasonably strong dataset for trend analysis. The fire data were pre-processed to filter out low confidence fire points only high-confidence fire detections i.e. confidence level > 50% were retained for analysis. The data was temporally aggregated to convert daily fire counts per year into annual counts per sub-biome, hence enabling long-term trend analysis.

3.2 Methodology

The methodology (Figure 2) employed in this study integrates several statistical and spatial analysis techniques to analyze the global trend in forest fire frequency and severity across a range of sub-biomes. The steps involved in the analysis are outlined below.

Data Preprocessing
This raw MODIS active fire data was filtered and aggregated. Only the fire detections with a higher confidence than 50% were retained to exclude false positives. The daily fire detections for each sub-biome were then aggregated into annual counts, which produced the time series of annual fire frequencies from 2001 to 2023.

Trend Analysis
Long-term variations in fire frequency and severity were traced using the Mann-Kendall test to apply trend analysis on fire counts and FRP time series within each sub-biome. The Mann-Kendall is a non-parametric test designed to identify monotonic trends within time series data (Mann, 1945; Kendall, 1948). It is particularly useful for environmental data, as it does not require the data to follow a normal distribution. In addition to the Mann-Kendall test, Sen’s slope estimator was used to quantify the rate of change in fire frequency and severity (Sen, 1968). The magnitude of the trend is given by the Sen's slope, an indication of whether increased/decreased fire activity over time happens. Both positive and negative slopes were identified across different sub-biomes, reflecting the variability of fire dynamics in different ecological zones.

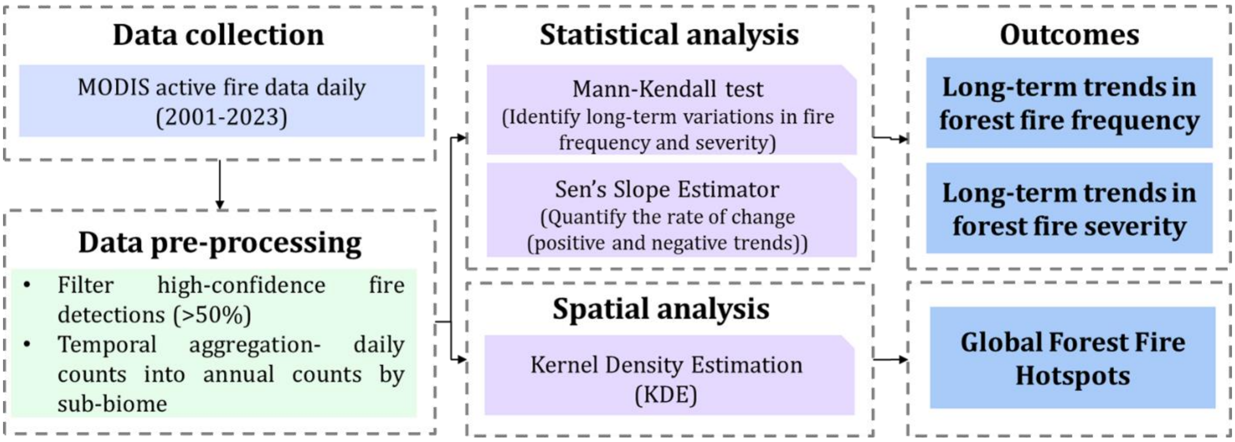

Figure 2. Methodology flow chart for the study

Spatial Analysis
Spatial mapping was carried out in order to visualize the fire activity distribution around the world. Kernel density estimation (KDE) technique was used to create the Forest Fire Occurrence Density Map for 2023. KDE is a non-parametric estimation of the probability density function of a random variable (Terrell, 1992), in this case, spatially distributed occurrences of fires. The result is a heatmap that highlights regions with the highest fire frequencies, providing a visual representation of global fire hotspots.

4. RESULTS AND DISCUSSION

4.1 Trends in Forest Fire Severity

The Mann-Kendall trend test revealed significant trends in forest fire severity across multiple sub-biomes (Figure 3(a)). Red and orange areas indicate regions where fire severity has strongly increased, whereas decrease is indicated by green areas. There is a sharp increase over the past two decades in fire severity in the Lowland Boreal Taiga (2a) across Canada, Alaska, and Siberia; deep red colors indicate intensifying fires within this sub-biome. These findings are consistent with the broader literature on climate change, which suggests that boreal and temperate regions are experiencing more frequent and severe fires due to rising temperatures and prolonged droughts (Li et. al., 2021; Wasserman et. al., 2023). Climate change has been one of the major drivers in this case, as higher temperatures and drier conditions have led to more severe fires burning with greater intensity and for longer periods (Abatzoglou et. al., 2017).

Similarly, in the Tundras of the Cryoro Belt (1c), fires are becoming more intense in previously fire-resistant landscapes, indicating a significant ecological shift due to warming climates. Temperate Deserts and Semi-Deserts (7b) of Central Asia and portions of the Middle East, exhibit increasing intensity, indicated by orange hues, likely due to increasingly arid conditions and rising temperatures, which enhance fire intensity. Regions like the Lauroid Evergreen Forests (4a) and the Conifer Coastal Forests (4b), particularly in California and parts of Southern Europe, show heightened fire severity, fueled by prolonged droughts and heatwaves.

The Tropical Pluviseasonal Forests (8b) and Tropical Xeric Shrublands (8a), particularly in Africa and Australia, show mixed trends. While some areas see increasing fire severity,

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others indicate a decline, which could be linked to change in rainfall pattern, fuel availability, and local fire management efforts (Barber et. al., 2023). Similarly, Grass-Steppe (8a) and Forest Steppe (6a) regions show mixed patterns of increasing and decreasing severity, depending on local climatic and environmental conditions.

The outcomes of this study provide valuable insights into the evolving fire regimes across global sub-biomes. The significant increase in fire activity in boreal and temperate regions can be attributed to a combination of factors, including rising temperatures, prolonged droughts, and changes in vegetation structure. Climate change has played a central role in exacerbating fire risk in these regions, as higher temperatures have led to drier conditions and increased the availability of fuel for fires (Moritz et. al., 2012; Johnstone et. al., 2016).

While other areas such as the Tropical Rainforests (9a) of Amazon Basin and Southeast Asia show significant decreases in fire severity, denoted by green areas on the map. The natural fire resistance properties of the rainforests and mutual conservation efforts enhance by the formulated fire management policies contributed to this reduction (Cochrane, 2003). The cause of the decline can be explained based on enhanced fire management practices, such as suppressing fires and installing early warning systems (Goldammer and Center, 2017).

Trend analysis of global forest fire severity provides a comprehensive view of the increasing severity of boreal and temperate subbiomes in which warming climates, dry conditions, and increases in fuel loads translate into higher severity fires. Conversely, fire severity tends to decline in tropical subbiomes, which could reflect either improved fire suppression or inherent ecosystem resistance.

4.2 Trends in Forest Fire Frequency

Analysis of long-term trend in forest fire frequency shows notable patterns around the global sub-biomes (Figure 3(b)). In the Lowland Boreal Taiga (2a), which covers vast areas of northern Canada, Alaska, and Siberia, there is a significant increase in fire frequency, indicated by the red hues on the map. This sharp rise in fire activity is largely driven by climate change-induced warming, which makes these regions drier, thereby making them prone to fires (Scholten et. al., 2024). Similarly, the Tundras of the Cryoro Belt (1c), traditionally fire-resistant due to their colder climates, are showing unexpected increases in fire events, suggesting significant ecological shifts (Choler, 2023).

In contrast, tropical regions like the Tropical Rainforests (9a) in the Amazon Basin, parts of West Africa, and Southeast Asia display a significant decrease in fire frequency, marked by the blue and light blue areas on the map. This decline could be attributed to the changes in land use patterns, such as the conversion of forested areas to agricultural land, which has reduced the availability of fuel for fires (Juárez-Orozco et. al., 2017).

The observed decrease in fire activity in tropical sub-biomes is likely linked to changes in land use patterns and fire management practices. In many tropical regions, deforestation and agricultural expansion have reduced the amount of forested land available for fires, while fire suppression efforts have helped to reduce the frequency and severity of fires. However, it is important to note that while fire activity may have decreased in tropical regions, the long-term impacts of deforestation and land conversion on biodiversity and ecosystem services remain a concern (Barber et. al., 2023).

Tropical Xeric Shrublands & Woodlands (8a) exhibits mixed trends in Australia and southern Africa, with some areas showing slight increases in fire activity. In the Lauroid Evergreen Forests (4a), Southern Europe and California, increasing trends are detected, attributed to long-term drought and heatwaves that have worsened through time (Dong et. al., 2019).

Other sub-biomes such as Forest Steppe (6a) in Mongolia and parts of Central Asia that show diverse trends, representing complex interactions among climate, land use, and fire activity. Temperate Deserts & Semi-Deserts (7b) in Central Asia and the Middle East also showed increasing trend, primarily due to drying climates and higher temperatures. The analysis highlights divergent trends in fire frequency, with boreal and temperate regions experiencing significant increases, while many tropical regions witness a decline in fire activity.

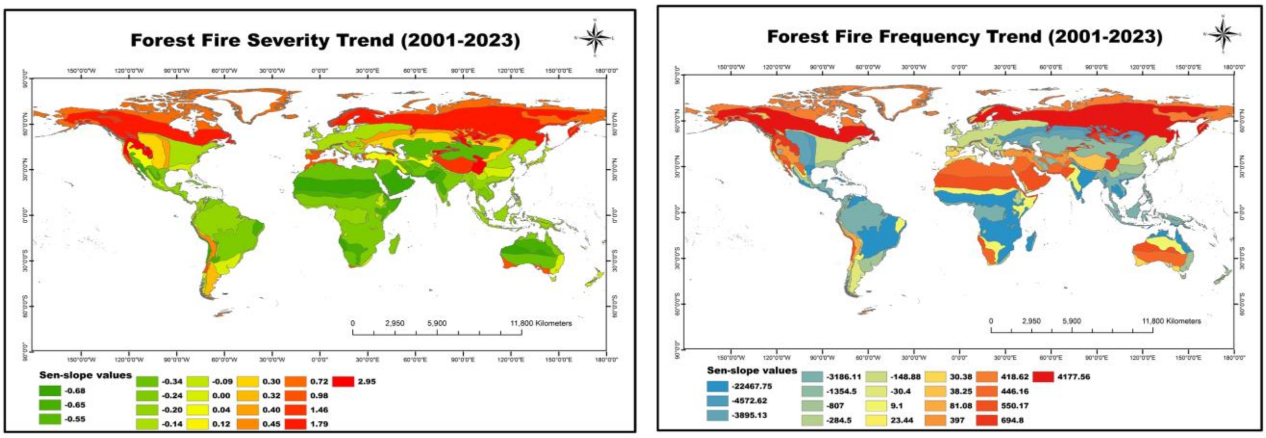

Figure 3. (a) Long-term trends of forest fire severity (2001-2023) **(b)** Long-term trends of forest fire frequency (2001-2023)

4.3 Spatio-temporal analysis of the forest fire occurrences

Figure 4 depicts the proportion of global forest fire occurrences across different sub-biomes from 2001 to 2023, providing valuable insights into the shifting patterns of fire frequencies in different ecosystems over the 23-year period.

Spatial-temporal analysis of forest fire events across different subbiomes from 2001 to 2023 shows that the largest contributor to global forest fires throughout the period is the tropical pluviseasonal forests and woodlands (8b), represented by the largest blue sections. On average, this sub-biome accounts for between 55% and 64% of global fire occurrences annually, making it the most fire-prone ecosystem during these years. In years such as 2013 and 2017, its contribution reached a peak of approximately 63.9% and 63.5%, respectively. Even in the years with relatively lower activity, such as 2001 (55.7%), the tropical pluviseasonal forests still contribute over half of all forest fire occurrences. This biome's sustained high percentage suggests that it faces persistent fire risks, likely influenced by human activities, such as deforestation and land-use changes, as well as climate-related factors, such as prolonged dry seasons and rising temperatures (Barber et. al., 2023).

The second most prominent sub-biome, the tropical rainforests (biome 9a), represented by the orange segments, show an increasing trend in fire occurrences over the years. In 2001, tropical rainforests accounted for about 8.1% of global fires, but by 2023, their contribution had risen to approximately 14.9%. This sharp increase reflects growing fire susceptibility in tropical rainforests, which were historically more resistant to fires due to their high moisture content. However, factors such as deforestation, agricultural expansion, and changing climate patterns (e.g., drier conditions and longer droughts) have significantly heightened fire risk in these once fire-resistant regions (Juárez-Orozco et. al., 2017).

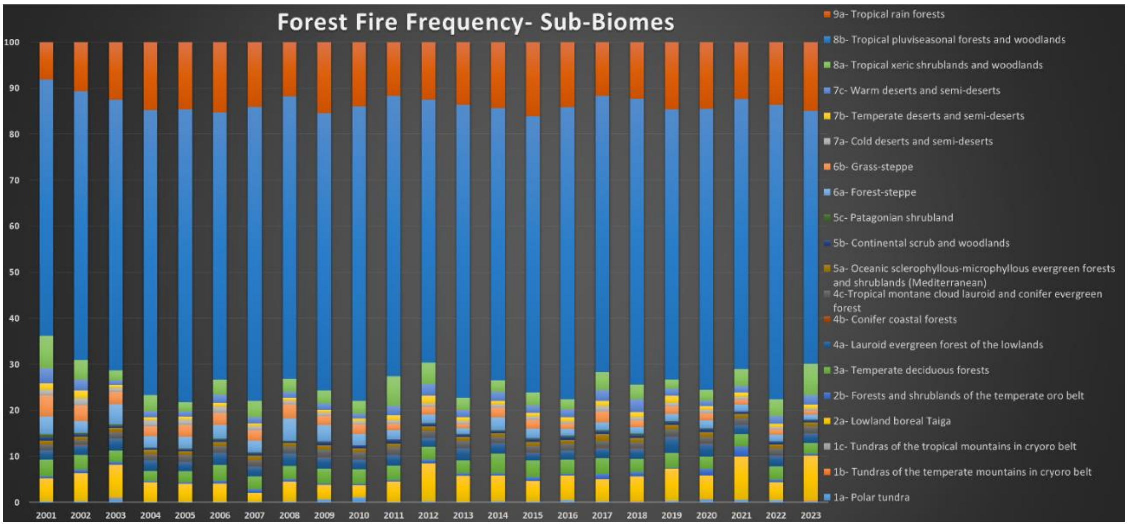

Figure 4. Spatial-temporal distribution of forest fire occurrences (2001-2023)

Other sub-biomes, including temperate deserts (7b), grass steppes (6b), and forest steppes (6a), have smaller but relatively consistent contributions to global fire occurrences. Combined, these sub-biomes typically represent around 2% to 10% of the total annual fire occurrences, with slight fluctuations year by year. Their more localized fire regimes indicate that fires in these regions are primarily driven by regional climate conditions, vegetation dynamics, and land-use patterns (Dong et. al., 2019).

In terms of temporal trends, there is a clear increase in the fire occurrences within tropical rainforests and warm deserts, especially in recent years, reflecting rising fire risks in these biomes (Scholten et. al., 2024). However, the contribution of tropical pluviseasonal forests remains relatively stable throughout the years, consistently accounting for the largest share of global fire occurrences. The overall trend points to a growing fire vulnerability in tropical and arid ecosystems, likely exacerbated by the effects of climate change and human interventions.

Forest Fire Occurrence Hotspot Analysis

The forest fire occurrence hotspot analysis for 2023 provides a detailed spatial representation of recent fire hotspots across the globe (Figure 5). The map highlights regions with the highest fire frequencies, including the Tropical rainforests (Sub-biome 9a), Tropical xeric shrublands (Sub-biome 8a), and parts of Africa and South America. These regions have experienced intense fire activity in recent years, with the highest densities observed in areas undergoing deforestation and land conversion (Garcia et. al., 2022). In South America, particularly in Brazil and surrounding areas, the Tropical Rainforests (9a) and Tropical Pluviseasonal Forests (8b) stand out as major fire occurrence zones. This is particularly concerning as these areas represent some of the most biodiverse ecosystems in the world (Torello-Raventos et. al., 2013). The high fire density is likely a result of deforestation, agricultural expansion, and drought conditions exacerbated by climate change. The central and southern parts of the continent, dominated by Tropical Xeric Shrublands (8a) and Grass-Steppes (6b), also show moderate fire activity.

In Australia, the Temperate Deserts and Semi-Deserts (7b) and Warm Deserts (7c) are clearly visible as fire hotspots. These regions, marked by frequent wildfires, experienced high fire frequencies in 2023, reflecting the vulnerability of semi-arid ecosystems to rising temperatures and prolonged dry spells. The fires in these regions are also likely fuelled by the highly flammable vegetation typical of arid environments (Ruscalleda-Alvarez, 2021).

In North America, particularly in the United States and Canada, the Lowland Boreal Taiga (2a) and Forests of the Temperate Oro Belt (2b) have seen significant fire activity.

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The boreal forests, stretching across Alaska and Canada, have become more prone to wildfires due to rising temperatures, changing precipitation patterns, and increased fuel loads (Li et. al., 2021). These regions, historically less fire-prone, now represent significant fire risk zones as global temperatures rise.

In Europe and parts of Asia, particularly in the Mediterranean Scrublands (5a) and Forests of the Temperate Oro Belt (2b), there are visible clusters of fire activity. The Mediterranean region, especially around southern Europe and parts of Turkey, has long been fire-prone due to its hot, dry summers and dense vegetation. The increasing fire density in these areas can be attributed to prolonged droughts and human activities like land clearing (Dong et. al., 2019).

Overall, forest fire occurrence hotspot analysis highlights the shifting dynamics of global forest fires, with regions in the tropics, boreal zones, and temperate forests showing high fire density in 2023. This underscores the need for targeted fire management strategies in these vulnerable sub-biomes, as well as broader global efforts to mitigate the underlying climatic drivers contributing to increased fire activity across diverse ecosystems (Robinne et. al., 2018).

The spatial analysis of fire hotspots provides further evidence of the complex interplay between climate, land use, and fire activity. Regions with high fire densities, such as the Amazon Basin and parts of Africa, are facing significant challenges in managing fire risk due to ongoing deforestation and land degradation (Hoffmann et. al., 2003). The findings highlight the need for integrated fire management strategies that consider both the ecological and social drivers of fire activity.

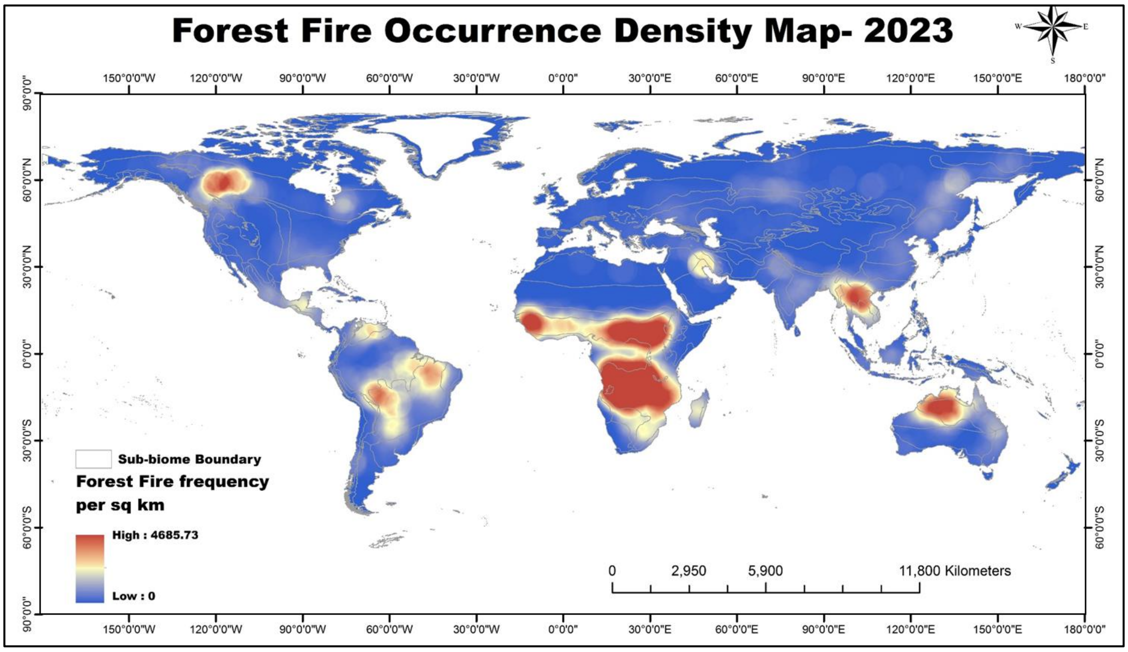

Figure 5. Spatial hotspot map of forest fire occurrences (2023)

CONCLUSION

This study provides a comprehensive assessment of global forest fire dynamics over the past two decades, offering valuable insights into the trends of fire severity and frequency across different sub-biomes. The combined use of MODIS active fire data, trend analysis techniques, and spatial mapping has allowed for a detailed exploration of how fire regimes are changing in response to climate change and land use patterns. The findings highlight the increasing fire risk in boreal and temperate regions, where rising temperatures and prolonged droughts are driving more frequent and severe fires. In contrast, fire activity has decreased in tropical regions, likely due to changes in land use and fire management practices. However, the continued loss of tropical forests through deforestation poses a significant threat to global biodiversity and ecosystem services.

The fire hotspots analysis for 2023 provides a valuable tool for identifying recent fire hotspots and prioritizing fire management efforts. The analysis highlights regions where fire activity is most intense, underscoring the need for targeted fire management strategies in these areas to mitigate the impact of recurrent fires. Overall, this study underscores the importance of continuous monitoring and assessment of forest fire dynamics to inform policy decisions and enhance global fire management practices. The findings provide a crucial foundation for understanding the impacts of forest fires on biodiversity, carbon cycling, and ecosystem services, paving the way for more resilient and adaptive strategies in the face of global environmental changes.

DATA AVAILABILITY

The study utilizes publicly available MODIS active fire points data which can be downloaded through the NASA Fire Information for Resource Management System website - https://firms.modaps.eosdis.nasa.gov/. The database prepared for this study can be provided upon request to the corresponding author.

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