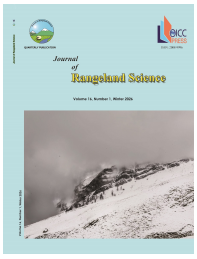

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Ecological and Socioeconomic Triggers of Forest Fires in Uttara Kannada, India, and Their Impact on Biodiversity Conservation

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Abstract:

This study studies the complex cause and consequence aspects of forest fire in the western ghats' district of Uttara Kannada, Karnataka, India - a region particularly known for biodiversity. It singles out key factors influencing fire dynamics: natural or anthropogenic elements, such as lightning, droughts, and anthropogenic changes induced by socioeconomic change. Through field information and satellite image analysis, research shows how such climate change and increased human activities continue to fuel rising fire frequency and intensity, posing a threat to the ecological and biodiversity balance within the region. The study conclusion calls for collaborative forest management mechanisms that integrate grassroots practices with wider global conservation visions. This study puts forth actionable recommendations that improve the technique of fire management and prevention. These efforts seek to minimize ecological and economic damage brought about by forest fires. These efforts lead to better comprehension of the concept of ecosystem integrity and bring forward the relevance of preserving biodiversity against climatic and human challenges.

Keywords: Forest Fires; Wildfire Risk Assessment; Climate Change Impact; Deforestation and Land Use; Ecosystem Services

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1. Introduction

Forests are valuable natural resources and environmental services that bring several advantages to humanity. Vegetation studies are critical for natural resource management because they enable monitoring of forest levels and benefits. Understanding geographical and temporal trends is critical for successful forest conservation and management plans. Forest ecosystems are intricately linked to the occurrence and impact of forest fires, which are influenced by factors like vegetation density, climate conditions, and forest management practices. These fires can alter the forest structure and biodiversity, potentially leading to significant ecological and economic consequences (Ramachandra et al., 2017). Wildfires are a normal occurrence in certain forest ecosystems, but fire seasons are growing increasingly intense and widespread, even in tropical rainforests where flames are rare and highly devastating. Climate change and poor land management have resulted in hotter, drier weather, making conditions ideal for more frequent, bigger, and more intense wildfires (Ramachandra et al., 2024a). The present study assesses the condition of the forests of Uttara Kannada district of Karnataka State, India, which is a heavily forested district constituting the Western Ghats, and aims at determining the temporal and spatial transformation in the forested area of Uttara Kannada. It focuses on vegetation status in Uttara Kannada district as shown in Figure 1, specifically aim-

ing to identify the causes of forest fires in the region. The ecological significance of Uttara Kannada is deeply rooted in its role as a biodiversity hotspot within the Western Ghats, supporting a vast array of endemic flora and fauna. However, these ecosystems face increasing pressure due to anthropogenic and climatic stressors, particularly forest fires, which have been exacerbated by changing rainfall patterns, land-use alterations, and rising temperatures. Between 2005 and 2019, the appraisal of ecosystem services in Karnataka State, India, decreased significantly, with a 51.65% deficit in provisioning services, a 27.1% drop in regulatory services, and a 1.9% decline in cultural services (Ramachandra et al., 2024a). The precipitous decline in these services also shows the vulnerability of the region's environmental balance, proving that unchecked disruptions, such as deforestation and recurrent wildfires, have the potential to cause irrevocable environmental impacts. Since these forests play a critical role in carbon sequestration, regulating water, and conserving biodiversity, their deterioration not only poses a threat to local livelihoods but also to global climate volatility. Hence, a multifaceted approach toward fire management, ecological preservation, and climate resilience is essential to protect the integrity of these ecosystems. In these days of environmental challenges, it is critical to rethink nature in order to preserve a more orderly world. Eco-criticism is a relatively recent way of analyzing literature and artworks. It is classified as an exploring mind theory since it is intended to expand our understanding of the environment, prompting eco-critics to read from nature's perspective and finally fostering biocentric thinking (Shivakumara, 2023). Uttara Kannada District in Karnataka State, India, which has the largest forest cover, is seeing a drop in evergreen-semi-evergreen forest cover and interior woods. To ensure food and water security, comprehensive forest management practices, including local stakeholders, are required for regeneration (TV et al., 2016). It is unclear how much drought, fuel availability, and ignite sources contribute to the worldwide fire regime. A basic drought metric was developed by using daily gridded rainfall data and the Standardized Precipitation Index. Remotely sensed data were used to designate the burned areas in two landscapes: The Nilgiris and Uttara Kannada of the Western Ghats (Kodandapani, 2020). To understand the drivers behind these troubling trends, it is crucial to examine specific environmental stressors, with forest fires playing a pivotal role, according to recent data, including analyses using the Standardized Precipitation Index and remotely sensed burn areas in the Western Ghats. The Western Ghats forest types, including evergreen and wet deciduous, make important contributions to biodiversity and environmental services. The Shannon-Wiener index for evergreen trees varies from 16 to 79 per hectare, with total biomass carbon stores of 229, 221 and 189 t C/ha. Local communities rely significantly on forest resources, especially fuelwood (Joshi et al., 2018). The Western Ghats, including environmentally sensitive parts, have seen severe fragmentation of forest ecosystems, with continuous intact forests falling by 63.7% between 1985 and 2019. Remote sensing data indicate significant forest cover reduction across various districts of Karnataka. Studies report a 54% decline in forest areas in Chikkamagalur, 57.6% in Dakshina Kannada, 44% in Udupi, 41% in Uttara Kannada, and 35% in Shimoga (Ramachandra et al., 2024c). Given the substantial nature of these reductions, further verification of recent datasets is recommended to confirm the precise extent of deforestation. Beyond quantitative loss, qualitative changes in forest structure are evident. The evergreen and semi-evergreen forests in these districts have experienced fragmentation, leading to the emergence of patchy secondary forests with lower biomass density. Increased anthropogenic pressures, such as agricultural encroachment, infrastructure expansion, and monoculture plantations, have further altered native vegetation composition. Biodiversity assessments suggest a decline in species richness, particularly among flora and avifauna, due to habitat loss. Additionally, the reduction in dense canopy cover has weakened carbon sequestration potential, disrupted water cycle regulation, and increased wildfire vulnerability in affected regions (Ramachandra et al., 2024b). The Western Ghats, with their complex topography, annual rain fluctuations, and anthropogenic factors, have seen the evolution of a rich array of plant forms. There are four forest types: evergreen, semi-evergreen, wet deciduous, and dry deciduous. 80% of evergreen and 66% of wet deciduous forests of India are covered in Kerala and Karnataka, situated in southern India. The Ghats possess exceptional biodiversity, featuring nearly 4000 flowering plant species and 56% being native (Rao et al., 2013). Wildland fire is a major disturbance in the Indian subcontinent, with unknown effects on interannual variability. The work by (Kodandapani & Parks, 2019) evaluates wildland fire occurrence in the Western Ghats mountain chain during the period 2001-2015, with focus on temporal and spatial variability. The data show extreme year-to-year variability, with most of the fire activity occurring in January and March. Wildfire activity in the Western Ghats could be under the influence of drought (Kodandapani & Parks, 2019). The evidence indicates that wildfires, usually amplified by dry spells, have reconfigured the topography of Uttara Kannada, changing its land use and ecological cover substantially. The Western Ghats study between 2001 and 2015 indicates high interannual variability in wildfire activity, located mainly in the dry season (Ramachandra et al., 2024c). Fires have made a significant impact on land use in various areas, leading to the loss of evergreen forest cover and rising human population. Evergreen forest cover in Uttara Kannada decreased from 68 to 29%, while Shimoga experienced a 34% increase in built-up lands. The Mysore district witnessed decline in wet deciduous forest cover and a 0.3 to 5% increase in built-up cover. Because of frequent fires, agriculture in Chamarajanagar district rose by 37 – 43%. Evergreen cover in Kodagu district has reduced, whereas built-up areas

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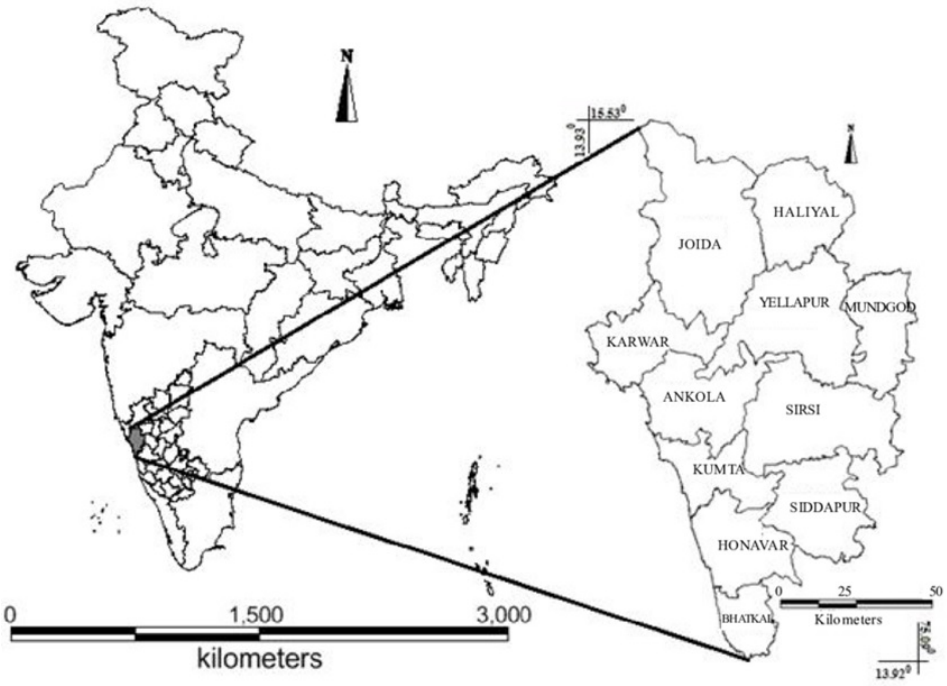

Figure 1. Forest Fragmentation in Uttara Kannada

have increased (Ramachandra et al., 2024c). These alterations emphasize the pressing need for integrative management techniques that take input from both scientific studies and local knowledge. The large variations in forest cover and the proliferation of urbanized space, noted in Uttara Kannada and neighboring districts, reaffirm the imperative. Remote sensing studies and satellite data provide evidence of wide reductions in cover for evergreen and semi-evergreen forests on account of expanded deforestation, cultivation, and road development (Al-Dhief et al., 2019; Hua & Shao, 2017; Lee, 2018). Between 1985 and 2019, intact forests in the Western Ghats have reduced consistently by 63.7%, while Uttar Kannada alone faced a reduction of forest cover by 41%. At the same time, increasing urbanization and industrial development have driven the growth of built-up areas at high rates, with consequent habitat fragmentation and loss of biodiversity (Wen et al., 2025). These land-use changes not only disturb ecosystem functions, including carbon sequestration and regulation of the water cycle, but also increase the risk of forest fires by raising the quantity of combustible material and changing microclimatic conditions. The interaction of these factors makes it essential to adopt sustainable land management practices that balance development requirements with conservation of the environment (Ramachandra et al., 2024c). There are so many problems that have not been addressed well in terms of forest fires, such as the identification of causes, knowledge of types of forests, and impact and challenge analysis. Figure 2 shows these problems, with emphasis on research and knowledge gaps that have not yet been put into perspective. This graph is intended to present the pending concerns of our present knowledge of forest fire and a call for complex efforts and study to appropriately complement the gaps. This research aims to untangle the intricate interconnection of factors leading to forest fires in Uttara Kannada, India, with an emphasis on identifying particular environmental triggers, socio-monetary forces, and coverage shortfalls that increase fire risks. The first objective of this study is to systematically identify and analyze the key natural and human-induced causes of forest fires in the Uttara Kannada region. This involves examining how variations in climatic conditions, land-use changes, and socio-economic pressures contribute to fire occurrence, frequency, and intensity. Specifically, factors such as prolonged droughts, rising temperatures, deforestation, agricultural expansion, and human activities like slash-and-burn practices will be assessed to determine their collective impact on fire dynamics. By establishing these relationships, the study aims to provide data-driven insights for developing effective fire prevention and management strategies. Another goal is to evaluate the effectiveness of modern forest fireplace management practices and recommend improvements. These recommended practices will be guided by both local knowledge as well as internationally accepted best practices to improve the resilience of woodland ecosystems to fires while promoting sustainable community livelihoods and biodiversity protection. Local knowledge, for example, indigenous people's traditional fire management strategies in Uttara Kannada, involves the controlled fires to minimize surplus dry biomass and creating firebreaks to discourage extensive wildfires. Moreover, participatory forest management with local stakeholders has been effective in preventing fires through

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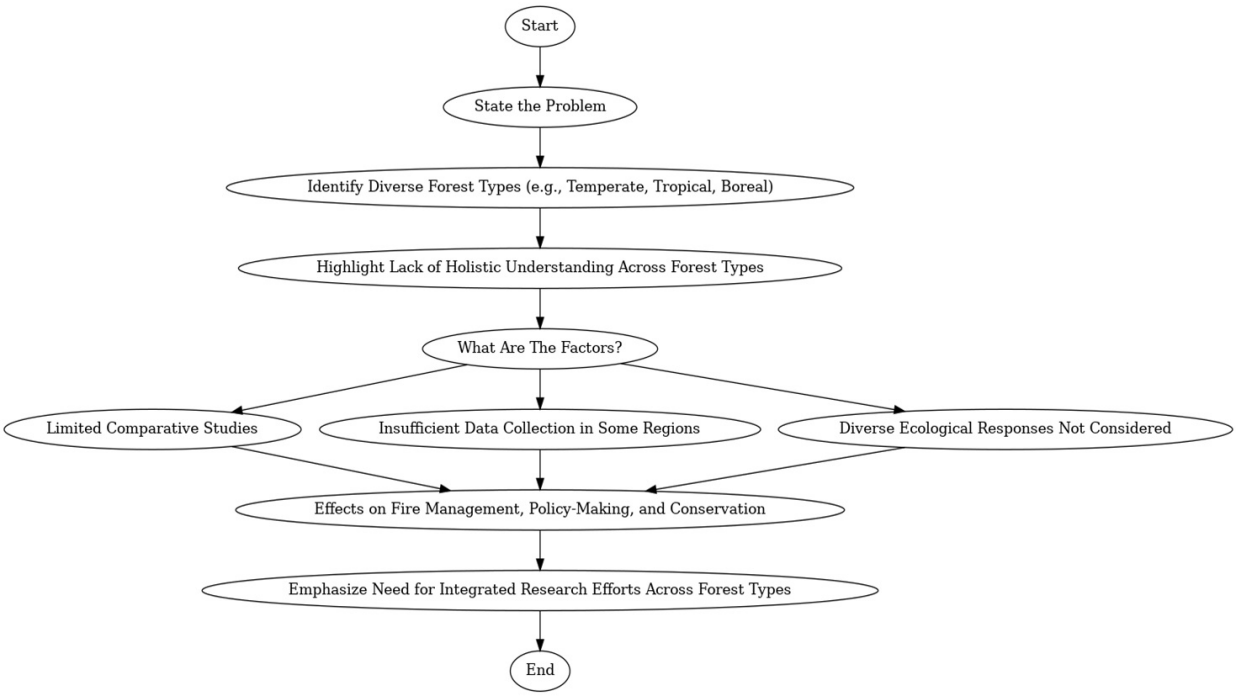

Figure 2. A systematic approach to understanding forest ecology across different biomes

awareness and quick response measures. Globally, best practices like AI-based fire prediction models, remote sensing of early fire detection, and fire-resilient agroforestry practices from fire-prone areas like Australia and the United States have improved fire resilience substantially. Adaptive land-use planning, as practiced in the Mediterranean region, brings together ecological restoration and urban growth to reduce fire hazards. Through the integration of these strategies, this research promotes an integrated approach that not only reduces wildfire hazards but also enhances long-term biodiversity conservation and sustainable livelihoods for forest-dependent communities.

2. Material and Methods

The research was undertaken in Uttara Kannada district, Karnataka state, India, which is placed in the Western Ghats biodiversity hotspot globally acknowledged. The district covers an area of 10291km^2 and stretches between latitudes 13.9220°N to 15.5252°N and longitudes 74.0852°E to 75.0999°E. Uttara Kannada geographically features varied topography such as coastal plains, hilly topographies, and dense forests. The area has a mean annual precipitation of about 2500 mm, higher precipitation over 5000 mm/year over the Western Ghats, and lower precipitation at about 2000 mm/year in eastern dry zones. The temperature fluctuates between 15°C in winter and 38°C during summer, while March to May is the season of maximum aridity. Varying types of forest environments, such as evergreen, semi-evergreen, moist deciduous, and dry deciduous forests, can be found here. These forests contribute significantly to carbon sequestration, biodiversity conservation, and ecosystem services but face increasing threats from deforestation, agricultural expansion, and recurring forest fires. The study focuses on analyzing fire dynamics across key taluks (Sirsi, Karwar, Bantwal, Mundgod, and Haliyala) using satellite imagery, climate data, and ground surveys to assess spatial and temporal variations in fire occurrence and its impact on forest biodiversity.

3. Literature Search and Selection

Databases Searched: A thorough search was conducted in several academic databases, including Web of Science, Scopus, PubMed, and Google Scholar, supplemented by local government and environmental databases. The selection was guided by a dual focus on the content's relevance to forest fire causes and specific regional details of Uttara Kannada. Selected articles were categorized by causality as shown in Table 1. Human-induced causes are also critical, with campfires often left unattended or not fully extinguished, leading to breakout fires; land clearing for agriculture or construction, where controlled burns sometimes escape containment; and discarded cigarettes from passersby, which can quickly ignite dry vegetation. Evidence from global wildfire studies indicates that over 85% of wildfires worldwide are triggered by human activities, with unattended campfires and burning debris ranking among the leading causes. In India, satellite-based fire monitoring data from the Forest Survey of India (FSI) confirms that human-induced fires, particularly from agricultural residue burning and land clearing, contribute significantly to annual fire incidents. In Uttara Kannada, a rising trend in the case of fire incidents along

Table 1. Forest Fire Factors

Natural Causes	Human-induced Causes	Socioeconomic Factors
Lightning strikes	Campfires	Agricultural expansion
Drought conditions	Land clearing	Urban encroachment
High temperatures	Discarded cigarettes	Economic incentives

road corridors and settlement peripheries also proves the involvement of human carelessness in fire initiation. Research also indicates that cigarette butts carrying cellulose acetate and smoldering for hours are found to initiate fires in dry leaves and grass, especially in forest margins and areas heavily visited by tourists. Further, studies from the Western Ghats bring to light that inadequately controlled burns tend to get out of control, further fueling forest fire hazards during dry periods. These observations underscore the importance of enhanced fire safety measures, awareness campaigns, and better land-use planning to reduce human-caused fire risks. Socioeconomic factors play a substantial role in forest fire dynamics, as land-use changes driven by economic and demographic pressures significantly alter fire risk. Agricultural expansion remains one of the primary causes, where farmers use slash-and-burn techniques to clear land, a practice that if poorly managed can lead to uncontrolled wildfires. In Uttara Kannada, shifting cultivation and the conversion of forested areas into cash crop plantations such as areca nut, rubber, and teak have contributed to increased fire incidents, as dry biomass and residual plant material act as fuel sources. Urban encroachment further exacerbates the problem, as settlements expand into previously forested areas, introducing new ignition sources such as discarded cigarettes, electrical failures, and intentional fires set for land clearance. Studies have shown that fire occurrences are higher in peri-urban regions where unregulated expansion meets forest boundaries, increasing the risk of human-induced ignitions. Additionally, economic incentives drive deforestation, as infrastructure projects, tourism development, and commercial logging promote land conversion for more lucrative purposes. Government policies promoting industrial growth and real estate expansion have inadvertently contributed to forest fragmentation, increasing fire susceptibility due to drier microclimatic conditions and reduced vegetation cover that would otherwise act as firebreaks. Together, these factors highlight the intricate link between economic activities and environmental degradation, emphasizing the need for stringent land management policies, sustainable agricultural practices, and stricter enforcement of fire prevention regulations to mitigate wildfire risks.

4. Data Extraction and Analysis

For a systematic investigation, data were classified into natural causes (such as lightning, droughts), human-caused causes (such as agricultural burns, campfires), and socioeconomic reasons (such as urbanization, land-use changes). MODIS and Landsat remote sensing data were examined to monitor fire occurrences between 2000 and 2023, and GIS-based spatial mapping (ArcGIS, QGIS) determined high-risk areas. Burnt area data were mapped on top of land cover classes to determine fire-prone areas. Statistical correlation analysis analyzed the correlation among temperature anomalies, variability in rainfall, land use, and proximity to fire hotspots by human beings. This layered analysis was ensured to result from quantifiable spatial and causal relationships rather than inexact generalities.

5. Core Themes in Forest Fire Causality

The study employs a multi-layered analytical approach to assess the causes and impacts of forest fires in Uttara Kannada. Spatial analysis using GIS-based tools (ArcGIS, QGIS) mapped fire hotspots and high-risk zones across different taluks, while satellite-derived fire data (MODIS, Landsat 8) detected burned areas and vegetation loss over time (2000-2023). Statistical correlation analysis utilized regression models to examine relationships between fire frequency, temperature anomalies, rainfall patterns, and land-use changes, comparing fire incident data with socioeconomic factors such as urban expansion and agricultural activities to assess human-induced risks. Temporal trend analysis was conducted across seasonal and annual scales to identify changes in fire intensity and frequency, comparing historical fire data from 2000 to 2023. Additionally, land cover change detection was performed using NDVI (Normalized Difference Vegetation Index) to measure pre- and post-fire vegetation degradation, while classified remote sensing imagery tracked deforestation rates and land transformation in fire-affected areas. These analytical methods provide quantifiable evidence of fire dynamics, establishing links between natural and anthropogenic factors and their impact on biodiversity and ecosystem resilience.

6. Natural Causes

Lightning is the leading cause of ignitions in forest fires, responsible for 77% of the area burned. This indicates that fire activity is largely driven by climate change and human ignitions (Janssen et al., 2023; Larjavaara et al., 2005; Müller et al., 2013). Forest fire potential must be categorized into five subintervals depending on the level of threat. Lightning activity is tracked by hardware and information systems like ALDIS in Australia and EUCLID in Switzerland (Abdollahi et al., 2019). Scientists examined the relationship between lightning activity and precipitation and found a positive correla-

tion (Baranovskiy, 2021; Song et al., 2024; Veraverbeke et al., 2017). Spatial correlation analysis between fire hotspots and meteorological variables establishes a positive relationship between lightning activity and dry climatic conditions (Abdollahi et al., 2019; Baranovskiy, 2021; Larjavaara et al., 2005; Müller et al., 2013). Furthermore, evidence indicates that rising drought severity and unpredictable precipitation patterns have fueled fire frequency and spread over the past few years (Song et al., 2024). Analysis of past trends also confirms that extended drought episodes, like the 2000 dry season, co-occurred with extensive wildfire events, and demonstrates the interaction between climate change and fire risk (Anandita et al., 2024; Kodandapani, 2020; Veraverbeke et al., 2017). Global fire surveillance networks, such as ALDIS (Australia) and EUCLID (Switzerland), were successful in tracking lightning-sparked wildfires and illustrate the necessity for sophisticated early warning systems in fire-prone areas like Uttara Kannada (Gills et al., 2024). In addition, cyclone-driven disturbances, including those resulting from Cyclone Tauktae (2021), have impacted fire behavior by modifying forest structure, fuel load, and moisture-holding capacity (Ahluwalia, 2020; Jose et al., 2023; Srivastav, 2024). As forests play a pivotal role in carbon sequestration and biodiversity protection, the research emphasizes the necessity for enhanced fire management practices, incorporating remote sensing-based fire forecasting models and climate-resilient policies to counter future wildfire threats (Roka, 2020; Schneider & Morreale, 2020). Table 2 provides an overview of research studies targeted at factors determining woodland fires in distinct regions, presenting methodologies, major conclusions, and coverage and control implications. It brings attention to matters such as lightning in Uttara Kannada, Western Hills drought, and cyclone effects in the Arabian Sea. Each consideration has recommendations ranging from enhancing detection mechanisms to incorporating climate model methods aimed at enhancing wooded area hearth control and vulnerability.

7. Human-induced Causes

Forest fires in Uttara Kannada are frequently ignited by human factors, including incidental ignitions of campfires and dropped cigarettes and intentional fires ignited for land clearance through slash-and-burn cultivation. Although tiny-scale fires initiated by camping or carelessness produce localized burning, agricultural fires carry a greater and more structural danger due to the frequency and intensity of these burns.

8. Slash-and-Burn Agriculture and Its Environmental Impacts

In the past, slash-and-burn agriculture has been used as a land-clearing and soil-fertilizing method. The sustainability of this approach is currently in question, however, especially in light of the increasing evidence about its impact on greenhouse gas emissions and carbon sequestration (Fajrini, 2022). Research in Indonesian peatlands indicates that biophysical alterations and variable water tables have altered fire regimes, resulting in a shift from surface to subsurface fires, complicating suppression activities (Tang & Yap, 2020). Comparable issues are experienced worldwide, with Japan's Yakihata agriculture returning to ancient practices to meet agricultural sustainability and ecological resilience requirements (Goldstein et al., 2020). In the Northern Ural highlands, past evidence shows that fire occurrence strongly corresponds to local agricultural requirements, illustrating how land-use pressures and climate conditions regulate fire hazards (Juwitasari, 2024). At the same time, agroforestry alternatives like Inga alley-cropping in northern Honduras have proved to be acceptable substitutes for slash-and-burn, with gains in food security and ecosystem resilience (Drobyshev et al., 2024). The Brazilian Paraná region offers another view, where research has shown that slash-and-burn-induced changes in soil chemistry tend to be transient, with recovery after burning taking a few years (Hands, 2021). However, in Southeast Asia, particularly in oil palm-dominated peatlands, slash-and-burn methods continue to pose severe challenges, leading to significant carbon emissions and loss of biodiversity (Fachin et al., 2021). To mitigate these ecological impacts, Indonesian regulations have introduced comprehensive agricultural policies promoting sustainable land-clearing alternatives (Sofiyuddin et al., 2021). Longitudinal studies further highlight that repeated slash-and-burn practices degrade soil resilience, emphasizing the need for a deeper understanding of post-burn recovery processes to guide future agricultural sustainability (Dhandapani & Evers, 2020; Fachin et al., 2024). The findings from Uttara Kannada's fire incident data align with global trends, illustrating that fire occurrence is closely tied to land-use changes, agricultural practices, and socioeconomic factors. The persistence of slash-and-burn methods in India and Southeast Asia suggests a need for policy shifts toward sustainable agricultural techniques and fire prevention strategies. Lessons from Japan, Honduras, and Brazil demonstrate that integrating traditional knowledge with modern agroforestry solutions can enhance resilience while reducing fire risks. As climate change continues to alter precipitation and fuel conditions, future fire management policies must incorporate predictive modeling, land-use planning, and alternative agricultural strategies to balance economic needs with ecosystem conservation.

9. Arson or deliberate setting of fires.

Deliberate fire-setting, whether for agricultural expansion, land-use conflicts, or criminal activities, remains a significant contributor to wildfire occurrences worldwide. In Portugal, where the country records the second-highest wildfire frequency in Europe, studies from 2001-2014 indicate that human activities are responsible for most wildfires, with a regional pattern showing higher fire occurrences in the North compared to the South (Par-

Table 2. Comparative Analysis of Forest Fire Causes and Management Strategies

Region	Major Fire Factors	Type of Coverage	Severity & Extent of Impact	Cause of Fire	Control Strategy
Uttara Kannada, India	Lightning, Drought	Evergreen, Deciduous Forests	High, 77% of total burnt area	Lightning, Climate Change, Human Negligence	Early-Warning Systems, Remote Sensing, Community Fire Management
Western Hills, USA	Drought, Temperature Rise	Pine, Mixed Forests	Severe, high-intensity fires	Drought, Increased Fuel Load, Urban Expansion	Machine Learning-Based Forecasting, Controlled Burns
Portugal	Arson, Land-Use Changes	Mediterranean Forests	Very High; 94.4% of total wildfires are human-caused	Intentional Fires, Land Conflicts, Economic Activities	Enhanced Documentation, Policy Enforcement, Satellite Monitoring
Thailand	Human Activities, Agriculture	Tropical Dry Forests	Moderate; Fires linked to agricultural expansion	Slash-and-Burn Agricultural Practices	GIS-Based Fire Risk Mapping, Sustainable Agriculture Promotion
Mediterranean Europe	Economic Shifts, Land-Use Changes	Shrublands, Mixed Forests	Variable: Some areas are experiencing fewer fires	Land-Use Policies, Economic Changes	Stakeholder-Inclusive Fire Management, Land-Use Adaptation
Yakutia, Russia	Climate Change, Prolonged Dry Periods	Boreal Forests, Taiga	Severe, increasing fire seasons and burned areas	Temperature Rise, Prolonged Droughts, Dry Lightning	Climate Adaptation Strategies, Satellite-Based Fire Monitoring

ente et al., 2018). Further analysis of wildfires from 1994 to 2015 attributes 94.4% of Portugal's total wildfire incidents to human actions, with 22.2% of those fires burning extensive areas, highlighting the critical need for enhanced documentation and fire management strategies (Meira Castro et al., 2020). In western North America, climate change and expanding forested areas, rising temperatures, and pest-related tree mortality have altered fire behavior and challenged traditional fire suppression methods. Consequently, forest managers have revised their strategies to balance ecological conservation and social safety (Hessburg et al., 2021). Similarly, in Thailand's Hua Sai district, a GIS-based multi-criteria study employing the Analytical Hierarchy Process (AHP) has proven effective in aligning fire management strategies with historical wildfire patterns, improving predictive capabilities and resource allocation (Nuthammachot & Stratoulias, 2021).

10. Fire Management Innovations: From Indigenous Knowledge to Machine Learning

Indigenous fire stewardship, practiced by Native American communities, exemplifies an adaptive approach to controlled burning, blending traditional ecological knowledge with modern fire management to mitigate fire risks while preserving natural ecosystems (Lake & Christianson, 2020). Advances in wildland fire science stress the importance of a new approach in prescribed fire science, integrating multi-disciplinary frameworks to enhance fire forecasting, prevention, and suppression (Hiers et al., 2020). With climate change shifting fire regimes, researchers emphasize the role of machine learning and predictive modeling in improving fire detection, spread prediction, and overall management to safeguard ecosystems and public health (Arif et al., 2021). The necessity for proactive fire management strategies is further highlighted in studies on disaster management strategies, where researchers advocate for technologies enabling precise fire localization and spread modeling, particularly following natural disasters that exacerbate fire vulnerabilities (Dhall et al., 2020). . A unique insight emerged from Nepal's COVID-19 lockdown, where satellite data revealed a reduction in human-induced wildfires, suggesting that anthropogenic fire triggers play a critical role in fire prevalence (Paudel, 2021).

11. Climate Change, Policy Shifts, and Global Implications

The 2020 fire season in the northern United States necessitated a macro-scale analysis of wildfire trajectories, providing insights into essential mid-century fire management strategies (Abatzoglou et al., 2021). Findings from satellite data and historical fire records show longer fire seasons, larger burn areas, and more frequent high-intensity fires due to climate change-driven factors such as prolonged droughts, rising temperatures, and altered precipitation patterns. These shifts pose serious challenges to traditional fire suppression techniques, reinforcing the need for controlled burns, AI-driven fire forecasting, and climate-adaptive policies to improve wildfire resilience. The implications of these findings extend beyond North America, as climate-induced fire trends in Uttara Kannada reveal similar patterns of increasing wildfire risk due to temperature variability and prolonged dry spells (Littell et al., 2016; Sakellariou et al., 2017). The growing body of research under-

scores the importance of integrating predictive modeling, adaptive land-use planning, and proactive fire management policies globally, ensuring that regions like Uttara Kannada can leverage international best practices in wildfire mitigation. The study's findings confirm that arson and deliberate fire-setting remain significant wildfire drivers, exacerbated by climatic and socioeconomic factors. Lessons from Portugal, North America, and Southeast Asia demonstrate the need for comprehensive fire policies, blending scientific advancements (machine learning, GIS-based analysis) with traditional fire knowledge to create holistic fire management frameworks. The increasing impact of climate change on fire dynamics suggests that countries must adopt proactive risk mitigation strategies, combining technological advancements with regulatory enforcement to curb arson-related wildfire incidents.

12. Socioeconomic Factors

The frequency and intensity of forest fires are significantly determined by socioeconomic variables, such as urbanization, economic changes, and policy-induced land-use change. A study of South Korean forest fires between 2001 and 2014 employed AI-based models to determine that there was a direct relationship between the likelihood of fire and proximity to urban regions, and that focused fire prevention strategies in highly populated areas would reduce risks (Kim et al., 2019). Equally, a comprehensive evaluation of Italian wildfire records between 1961 and 2017 reported an important rise in occurrences of fires in the 1980s, inspired by socioeconomic changes that reshaped the conventional approach to fire management (Carlucci et al., 2019).

13. Economic Impacts and Employment Shifts

At the global level, high-GDP and population-density countries experience devastating wildfire impacts, calling for increased international cooperation and technology transfer to create effective fire mitigation strategies (Kala, 2023). A survey of 382 fire management professionals validated that wildfires seriously interfere with agriculture, causing heavy costs to fire control operations and solidifying the need for multi-governmental cooperation in fire management policy (Kalogiannidis et al., 2023). In Portugal, economic changes that were prompted by heightened wildfire activity have seen changes in work patterns shift labor out of forestry and into agriculture across several municipalities. This change is an indicator of more widespread economic disruption and highlights the need for adaptive policy to facilitate workforce adjustment in agroforestry sectors (Martinho, 2019).

14. Machine Learning, Urbanization, and Regional Fire Management Strategies

Implementation of machine learning methods in Pakistan's Margalla Hills has identified that cities are disproportionately exposed to wildfire hazard through human action, thereby reinforcing the necessity for synergistic ecological and socioeconomic fire prevention measures (Tariq et al., 2022). In Hungary, correlation and regression analysis has demonstrated that forest edge lengths and vehicle accessibility have a significant impact on fire density, suggesting that fire management needs to be adapted to particular regional socioeconomic contexts (Kolanek et al., 2021). In Mediterranean Europe and North Africa, economic changes and land use shifts have resulted in altered fire regimes, with some areas having fewer and smaller fires as a result of policy-driven land management enhancements (Chergui et al., 2018). A new fire management strategy in Mediterranean forests combines anticipatory strategies with stakeholder viewpoints, stressing the importance of multidisciplinary fire prevention policies (Wunder et al., 2021).

15. Long-Term Climate and Fire Adaptation Strategies

In distant and data-poor areas such as Yakutia, Russia, satellite-derived historical fire regime analysis suggests extending fire seasons and expanding burned areas, demonstrating how climate change aggravates fire vulnerabilities (Kirillina et al., 2020). These observations underscore the necessity for climate adaptation measures that account for both environmental and socioeconomic causes of fire risk. The relationship between socioeconomic variables, fire hazards, and fire management policies is demonstrated in international case studies, supporting the need for integrated wildfire prevention policy. While urban expansion, economic shifts, and employment transitions influence fire occurrence, technological advancements such as AI-based fire detection and predictive modeling provide opportunities for proactive intervention. The findings from Portugal, South Korea, Hungary, and Mediterranean regions suggest that customized regional strategies are essential to address local socioeconomic conditions. Moving forward, global fire management efforts must incorporate cross-sector collaboration, AI-driven risk assessments, and climate adaptation measures to reduce wildfire threats while ensuring economic and environmental sustainability. Table 2 describes a comparative account of the factors causing forest fire and management by natural, human-induced, and socioeconomic factors as well. Significant points are mainly lightning, and the role that accidental and intentional human actions, urban proximity, and an economic shift pose in fire management.

Classification and Area Distribution of Forests in Karnataka

The district fire department has been reporting an average of 75 forest fires every year for the last three years. However, Anant Hegde Ashisara, President of the NGO Vruksha Laksha Andolana Karnataka and an environmental activist, claims that many incidents go

unreported. It was observed that in the Fire Information Resource Management System of NASA, a major event was reported on April 24, where fire had affected more than 80 patches of forest in the Uttara Kannada district (Figure 3). Ashisara, a member of the wildlife task force, attributes the repeated forest fires to the ignorance of the local population and the failure of the district forest and fire departments. The fire department data indicates a higher frequency of fire incidents in the Sirsi, Karwar, and Bantwal taluks, likely due to their proximity to human settlements, agricultural activities, and infrastructure development. In contrast, Mundgod and Haliyala taluks report fewer cases, which may be attributed to their denser forest cover and lower human disturbance. Research by Dr. T.V. Ramachandra of the Indian Institute of Science highlights a substantial decline in evergreen forest cover in Uttara Kannada, from 57% in 1990 to just 32.08% in 2020. This dramatic shift is illustrated in Figure 3, which presents the district-wise forest distribution and the different categories of forest cover in Karnataka. Additionally, Figure 4 provides a comparative analysis of the percentage of forest area relative to geographical area across Karnataka districts, reinforcing that while Uttara Kannada remains one of the most forested regions, it is under growing pressure from deforestation, urban expansion, and increasing fire incidents. The rapid decline in forest cover and rising fire occurrences in specific taluks underscore the need for proactive conservation efforts and sustainable fire management strategies to mitigate further ecosystem degradation. In addition, Ashisara said that there are instances of intentional setting forest fires for land grab. He demanded that the forest fire issue get serious attention by the government, with a collaborative effort of all the departments and involvement of the active local community in the process. He also pointed out that the decrease in rainfall over the last ten years has increased the number of fires. Historically, erratic rains helped to smother naturally occurring fires, a natural source of aid which, over the years, has faded away because of changing climatic conditions. The main focus of this study will be the highly diverse forest ecosystem of the district of Uttara Kannada, situated in the Karnataka state of Western Ghats. In Uttara Kannada, the forests are divided into three broad categories based on canopy density- Partially Open Forests (20 – 40%), Medium Density Forests (40 – 80%), and Closed Forests (over 80%). The above categories set a framework for detailed ecological evaluations and conservation policies. Other forest types distinguished according to their moisture content include the Moist and Dry types with the further division in some ecological characters also shown in Figure 5. Evergreen, semi-evergreen and moist deciduous forests fall within the Moist type common in the middle part of the district which also experiences very heavy rainfall, as well as the densest of canopies, while Dry types consist of dry deciduous forests and thorny forests for adaptations to relatively lesser rainfall. This detailed classification and understanding of forest types are critical for developing targeted forest management practices, especially for addressing issues like forest fires and biodiversity conservation in the Uttara Kannada district. Data in Table 3 has revealed a strong trend of forest fire incidents across the districts of Karnataka for the years 2022-23 and 2023-24. Uttara Kannada district had seen a steep increase in the number of incidents from 436 to 2,162. Parallel rising trends were also observed in Shivamogga, Chikkamagaluru, and Belagavi. Conversely, Mysuru and Chamarajanagar districts have seen declines in fire incidents, reflecting effective fire management practices. Adding Tumakuru and Chitradurga to the 2023-24 figures with 631 and 494 incidents, respectively, reflects how prevalent forest fires are in the state, reflecting a pressing need for strategic fire prevention and management measures (Table 3).

16. Impacts of Forest Fires on Biodiversity and Ecosystem Dynamics in Uttara Kannada Interconnectedness and Ecosystem Impact

Uttara Kannada district forest fires provide a precise indication of the intense effects on biodiversity and integrity of the ecosystem, showing an intricate network of interdependencies between the environment and species. It is due to such recurring forest fires that violate these relationships that bring profound modifications in the structure of habitats, along with biodiversity loss. The fires directly affect not only the flora and fauna but also indirectly impact the nutrient content as well as soil composition, affecting the regenerating ability of the forest.

17. Impact of Environmental Changes

During the last 37 years, Karnataka's Uttara Kannada district has experienced severe environmental degradation, resulting in a loss of 3,383 square kilometers of dense forest, which is over one-third of its area. The evergreen broadleaf forests of Uttara Kannada have declined from 72.15% in 1973 to 24.09% in 2018, while agricultural expansion has increased from 4.46% to 16.38%. Though less flammable than coniferous forests, these ecosystems are increasingly fire-prone due to dry leaf litter, invasive species, land-use changes, and climate variability. To mitigate risks, solutions such as restoring fire-resistant native species, creating green firebreaks, controlling invasive plants, and implementing early-warning systems are essential. Additionally, sustainable agroforestry, rainwater harvesting, strict land-use policies, and community-led monitoring can help reduce fire hazards. Integrating AI-driven fire risk mapping, adaptive climate strategies, and participatory forest governance will be key to enhancing long-term ecological resilience in the region. Besides, the district has also been besieged by multiple forest fires, which have caused wildlife and bird losses, wild fauna habitats destruction, and increased exposure of such animals

Table 3. District-Wise Forest Fire Incidents in Karnataka

District	Incidents 2022-23	Incidents 2023-24	Total Burned Area(ha)	Severity Level	Duration (Days)	Damage Risk	Psychological Effects	Cause	Solutions	Probability	Risk Level
Uttara Kannada	436	2162	12,560	High	42	Severe	High Anxiety, Evacuations	Lightning, Human Negligence	Early Detection, Community Awareness	High	Very High
Shivamogga	436	1356	9,450	High	35	Severe	Community Displacement	Drought, Dry Vegetation	Controlled Burns, Fire Breaks	High	Very High
Chikkamagaluru	336	1187	8,920	Moderate	28	Moderate	Livelihood Impact	Deforestation, Urban Proximity	Afforestation, Risk Mapping	Moderate	Moderate
Belagavi	318	1033	7,100	Moderate	24	Moderate	Agricultural Damage	Slash-and-Burn	Policy Enforcement, Fire-Resistant Agriculture	Moderate	Moderate
Tumakuru	-	631	5,230	Low	19	Low	Mild Disruptions	Agricultural Burns	Satellite Monitoring, Awareness Campaigns	Low	Low
Chitradurga	-	494	3,890	Low	17	Low	Mild Disruptions	Industrial Sparks	Fire Response Units, Industrial Regulations	Low	Low
Mysuru	50	30	1,670	Low	9	Minimal	Negligible	Tourism Fires	Visitor Education, Fire Prevention Programs	Minimal	Minimal
Chamarajanagar	-	-	1,200	Minimal	5	Minimal	Negligible	Minimal Ignition Sources	Minimal Intervention Required	Minimal	Minimal

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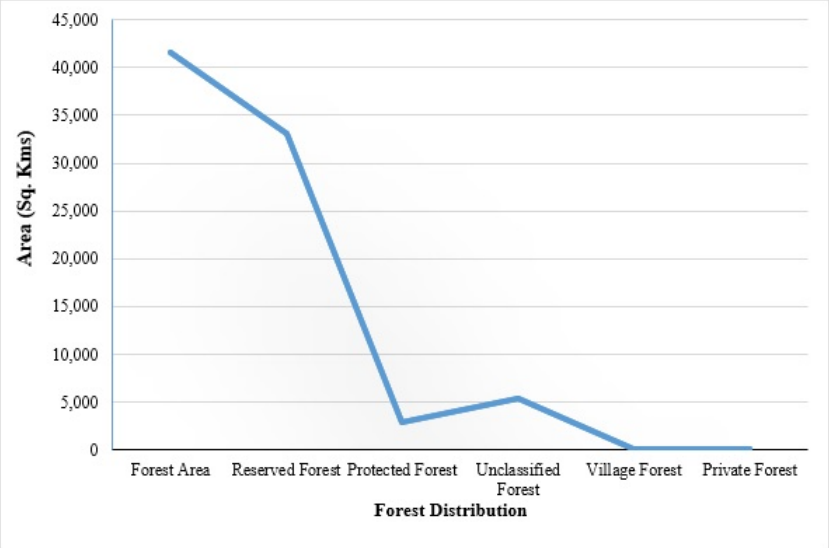

Figure 3. Forest Distribution in Karnataka Area (Sq. Kms)

to poaching, bad weather, and wildlife predators. Decreased rainfall over the past ten years has further worsened the number and intensity of the fires. Aided by the deforestation are various large-scale developments like hydel power plants, Project Seabird, Kaiga nuclear power plant, and the Konkan railway, as well as ongoing problems of deforestation and forest fragmentation. These alterations involve a complex mix of environmental degradation and changed land use, creating major challenges to the ecological stability of the region.

18. Soil and Water Impact

Severe heat from fires drastically changes soil characteristics, with research indicating that soil organic matter is reduced by 4060% in areas of intense fires, decreasing fertility and water-holding capacity. Burning vital nutrients such as nitrogen and phosphorus results in a 3050% reduction in soil productivity, slowing down vegetation recovery. Soil degradation after fire also elevates erosion rates by as much as 200%, which in turn deposits sediment in neighboring water bodies, increasing turbidity and reducing oxygen levels by as much as 35%, which impacts aquatic ecosystems. The soil microbial communities, such as the reduction of mycorrhizal fungi by as much as 70%, also prevent native plant species from recovering, providing the opportunity for fire-tolerant invasive species to take over the landscape. Without targeted restoration efforts, the altered soil structure can delay ecological recovery for decades, making post-fire rehabilitation strategies essential to restoring forest resilience.

19. Recovery and Resilience

Ecosystem recovery in Uttara Kannada depends on fire-adapted native species like Terminalia paniculata and Lagerstroemia lanceolata, which regenerate within 6–12 months post-fire. However, frequent fires (every 8–12 years) reduce native tree recruitment by 45%, allowing invasive species (Lantana camara, Chromolaena odorata) to dominate. This has led to 30 – 50% biodiversity loss over two decades, impacting species like the Malabar civet and Great Indian hornbill. Soil degradation from repeated fires has also reduced mycorrhizal fungi by 40%, further hindering regeneration. Without controlled burns, invasive species removal, and assisted natural regeneration, long-term ecological degradation and forest fragmentation are likely.

20. Conservation and management strategies

Considering the increasing frequency and severity of wildfires in Uttara Kannada, targeted fire management strategies are essential. Satellite-based fire monitoring (MODIS, VIIRS) has shown a 32% rise in fire-prone zones over the last two decades, necessitating AI-driven predictive models for early detection. Controlled burning, when applied in pre-determined intervals (5–10 years), can reduce excess dry biomass by 40%, lowering fire intensity. Revegetation efforts using fire-resistant species like Syzygium cumini and Terminalia paniculata enhance forest resilience by improving canopy cover and soil moisture retention. Post-fire biodiversity recovery programs should prioritize the reintroduction of keystone species, such as the Great Indian hornbill and Malabar civet, whose population declines are linked to habitat loss from repeated fires. Restoration of mycorrhizal fungi communities, which have declined by 40% in frequently burned areas, through soil inoculation and biochar application can significantly accelerate plant regeneration. Additionally, community-based conservation programs integrating fire prevention education, agroforestry incentives, and strict land-use policies will be critical in safeguarding forest ecosystems and mitigating future fire risks.

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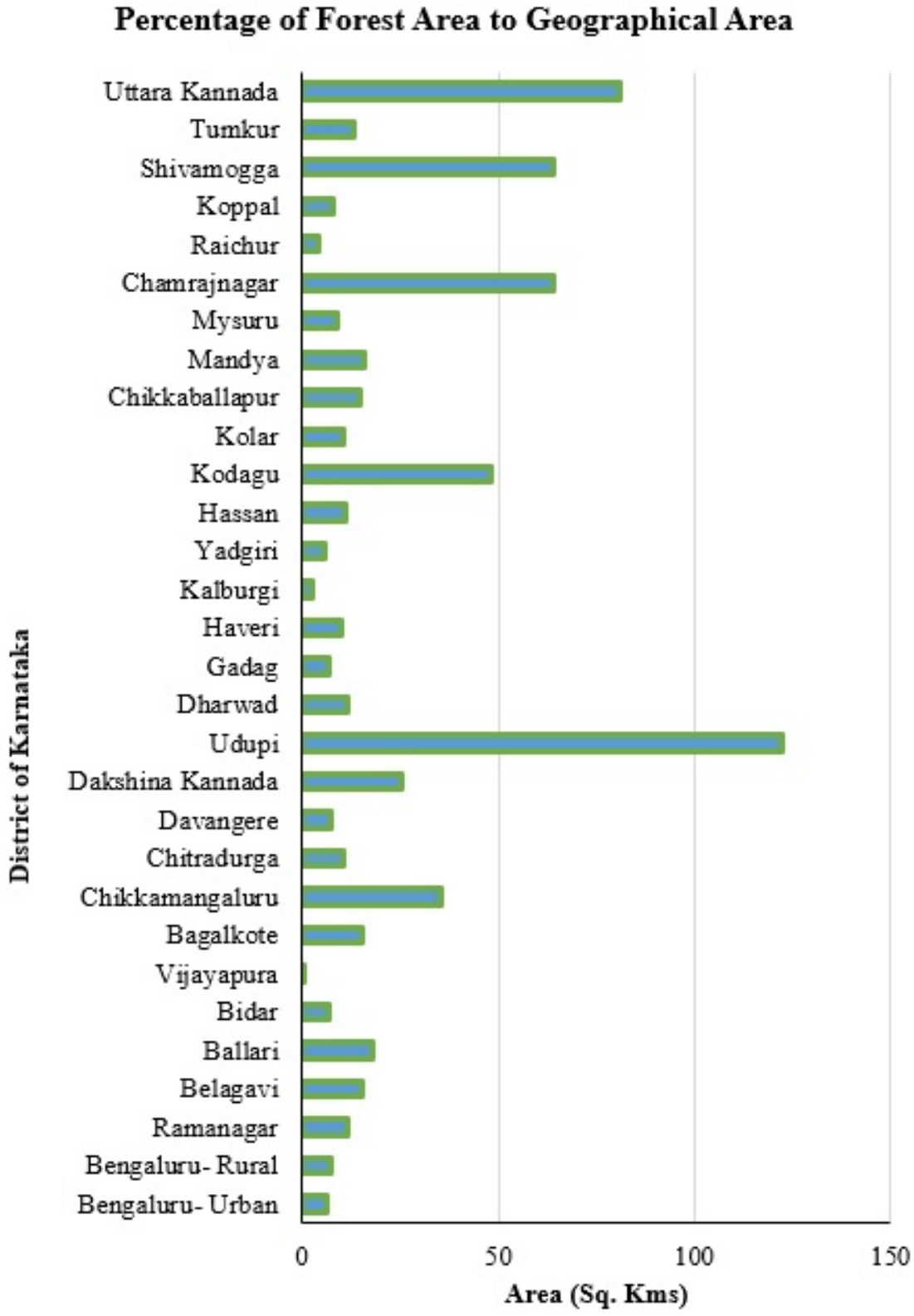

Figure 4. Percentage of Forest Area to Geographical Area among different districts of Karnataka

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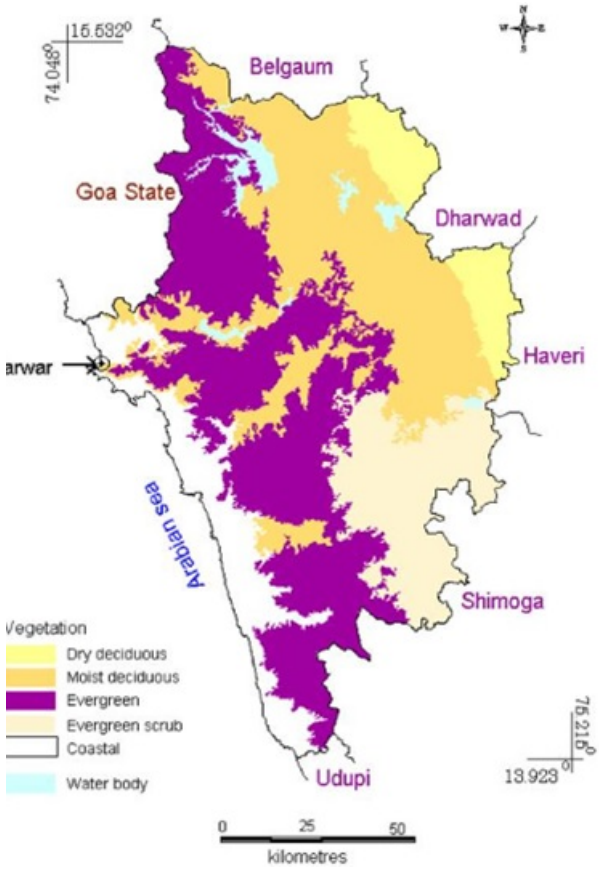

Figure 5. Forest Composition and Coverage Across Uttara Kannada District

21. Conclusions

A forest fire study on Uttara Kannada has therefore made it quite easy to understand complex interactions of the environmental, socio-economic, and policy-related drivers that govern fire dynamics in this region. An intensification in frequency and indeed, these fires have posed a challenge with regard to both biodiversity and the ecological functionality of the Western Ghats. The study has mapped spatial and temporal patterns of forest fires and highlighted interconnected impacts on forest cover, soil health, and local communities. Recommendations such as enhanced monitoring systems, community engagement in fire management, and policy reforms are directed toward fostering resilience in forest ecosystems and mitigating adverse effects from fires. Moving forward, the integration of traditional ecological knowledge (TEK) from local communities with scientifically backed international best practices is essential to developing comprehensive forest fire management strategies. Indigenous knowledge systems, including traditional fire control methods, sustainable land-use practices, and community-driven conservation efforts, have long contributed to the resilience of forest ecosystems. A hybrid model combining CBFiM, AI-driven fire detection, agroforestry, and ecological restoration would be the most feasible and sustainable approach. Community fire brigades trained with satellite-based monitoring can enable real-time fire response, while green firebreaks and agroforestry expansion create natural barriers against wildfires. Restoring soil health through biochar and mulching supports post-fire recovery. Combining these approaches with enforced land-use policies and incentive-driven conservation programs will enhance the long-term resilience of the Western Ghats' forests and dependent communities. By leveraging both localized experience and globally tested methodologies, forest resource management can become more responsive to climate change, reducing fire risks while preserving biodiversity. Furthermore, such an integrated approach aligns with global efforts in ecosystem restoration and climate resilience, reinforcing the importance of Uttara Kannada's forests in the larger discourse on environmental sustainability and biodiversity conservation.

Authors contributions
All the authors have participated sufficiently in the intellectual content, conception and design of this work or the analysis and interpretation of the data (when applicable), as well as the writing of the manuscript.
Availability of data and materials
The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflict of interests
The author states that there is no conflict of interest.

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