Ecological impacts of forest fire on composition and structure of Tropical Deciduous forests of Central India

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Acknowledgements

The authors acknowledge Forest survey of India (FSI), NASA-MODIS active fire data for providing open- access data. acknowledge the financial support provided by the DBT, Ministry of Science & Technology, Government of India in the form of R&D project (grant number BT/ PR12899/NDB/39/506/2015 dated.20/06/2017). The authors acknowledge the support provided by the Madhya Pradesh Forest Department during field survey and validation.

Abstract

The present study highlights the forest fire hotspots based on daily forest fire occurrence during 2000-2020 and its subsequent long-term impacts on different vegetation types in Central India. The MODIS (MCD14DL) based study exhibited the recurrence of fire incidences in central and southern parts of forests and affected substantial parts of the deciduous broadleaf forest (31.56% of select forest type) and deciduous needleleaf forest (30.23%), shrubland (7.52%), mixed forest (9.80%), with the major forest fire peaks during March and April, while negligible fire incidences were observed in plantation and grassland. 72% of field transects (157 out of the 218 field transects) were observed under high anthropogenic influences as evidenced by a large number of cut stumps. Six species (out of 106 studies tree species) including *Tectona grandis* L.f. (occurrence in 98% of fire hotspots), *Butea monosperma* (Lam.) Taubert (66%), were observed to be highly fire-resistant, recorded in >50% of the forest fire hotspots regions. The major forest fires hotspots (p<0.01) were observed in the Malwa plateau, Vindhyan ranges, and Satpura range during 2000-2020, as observed with high fire intensity. While the forest in the northern parts attributed a cold spot with reference to forest fires (p<0.01). The study elucidated the high susceptibility of forest fire in deciduous forests in Central India and necessitated proper management of forest fires by encouraging fire-resistant species, and prioritization of regions under fire hazards through the adoption of preparedness and response strategies to minimize the forest fire impacts.

Keywords: Forest fire frequency, Hotspots analysis, Tropical dry deciduous forest, Geoinformatics.

1. Introduction

A forest is a complex ecosystem and a repository for a wide array of life forms, mostly woody ones like trees and shrubs with a closed canopy and non-woody ones like herbs, grasses, and climbers in the ground layers (Pew & Larsen, 2001). The abundance of bacteria and fungi in forests led to the decomposition of dead organic matter thereby enriching the soil (Niraula et al., 2013). India is characterized by a wide variety of forest types, including tropical evergreen or rainforests, semi-evergreen forests, tropical deciduous forests, montane subtropical and temperate forests, and alpine scrub (Kodandapani et al., 2009). The forest in Central India, primarily the state of MP, holds the largest forest cover in the country (77482 sq. km *i.e.,* 25.14% of its total geographic area against 21.67% of the national average (FSI, 2019). Tropical dry deciduous forests (88.65%), tropical wet deciduous forests (8.97%), and tropical thorn forests (0.26%) are the three main groups of forests found in MP, each of which has different physiognomic and structural characteristics (Champion & Seth, 1968) (**Figure 1**). On the other hand, 5A/C1b Dry teak forests (26.4%) and 5A/C3 Southern dry mixed deciduous forests (24.55%) make up the majority of the 22 major forest types of MP. Recently, a new classification of forest types based on the current ecological, climatic, bio-geographic, and edaphic influences on the vegetation composition and stand formation has been proposed that is related to tropical moist deciduous forests (*Shorea robusta* forest), tropical dry deciduous forests (*Tectona grandis* dry forest), and dry deciduous mixed forests in Central India (ICFRE, 2013; Bahuguna et al., 2016). Moist deciduous forests of India are comprised of a range of deciduous tree species including *S. robusta, T. grandis, Madhuca longifolia, Boswellia serrata, Chloroxylon swietenia, Diospyros melanoxylon,* and *Syzygium cumini*, having moderate to thick bark and high coppicing ability (Reddy et al., 2007).

However, a variety of anthropogenic and natural phenomena, including timber felling, lopping, logging, fire, flash flood, and drought, are responsible for small to large-scale destruction and degradation of forests (Bowman et al., 2009; Gatti et al., 2022). Fire incidences significantly affect the structure, composition, and productivity of forests (Bond & Keeley, 2005), which led to spatio-temporal changes in forest regeneration (Vogelmann et al., 2012). Although the rate of deforestation has decreased over the past three decades, ~420 Mha of forest have been lost due to the conversion to other land uses since 1990, and >100 Mha of forests are adversely affected by forest fires, pests, diseases, invasive species, drought, and extreme weather events (FAO and UNEP, 2020). Around 6.58 Mha of Indian forests were fire-affected (FSI, 2019) that are mostly influenced by anthropogenic activities (slash and burn agriculture and various household interferences), topographical, climatological, and demographic aspects (Hiremath & Sundaram, 2005). A total of 64.84% of the total forest cover of Madhya Pradesh (MP) is fire-prone, of which 0.14% are extremely fire-prone, 3.79% are very highly fire-prone, 11.87% highly fire-prone, 19.36% are moderately fire-prone, and 19.36% less fire-prone forests (FSI, 2019). Forest fire causes devastating loss and irreparable damage to the environment and atmosphere through the abundant release (30%) of CO_2 (Satendra & Kaushik, 2014). The intensity and frequency of forest fires used to be influenced by a range of meteorological elements including drought, temperature, and wind speed (Tošić et al., 2019) together with a number of anthropogenic factors including forest dependency by a huge rural population for a range of sustenance goods (Carmo et al., 2011). The forest composition in terms of fuel load, fuel continuity, and inherent moisture content, plays a significant role on fire risk (Saura-Mas et al., 2010). Forest fires lead to significant perceptible change that hampers the ecosystem's goods and services, with significant cascading effects on forest biodiversity and changing climate (Thompson et al., 2013). Climate change has an influence on local weather events since it raises summer temperatures and alters the rainfall patterns considerably (Kirschbaum & Fischlin, 1996), while other dependent variables including wildlife and anthropogenic activities augmented the challenges of maintaining the forest ecosystem (Harrison et al., 2010; Kumar et al., 2020). Nevertheless, the fire regimes affected the distribution, structure, composition, and ecology of forests with varied intensities (Kirschbaum & Fischlin, 1996).

The growing severity and spread of forest fires in Asia were primarily due to rising temperatures and declining precipitation in conjunction with major land-use changes (Krishna & Reddy, 2012; Kodandapani, 2013). The advancement in remote sensing sensors (LANDSAT, AWiFS, SPOT, Sentinel 2, AVHRR, MODIS) having vivid spatial and temporal fidelity, contribute significantly to developing insights into forest fire genesis, its detection, forecasting, damage assessment, natural recovery, and regeneration (Eva & Lambin, 2000; Singh et al., 2002). Forest fire variability in terms of size, frequency, and severity is mostly due to deliberate and unintentional human disturbances including intensive grazing activities, collection of fuelwood and non-timber forest products (NTFPs), *etc*. Geoinformatics techniques for fire monitoring have a distinct advantage over traditional methods in terms of dependability, cost-effectiveness, speed of review, and high precision (Csiszar et al., 2006; Kumar et al., 2017). Operational fire monitoring through MODIS based fire mapping, European Forest Fire Information System, Canadian Wildland Fire Information System, and Indian Forest Fire Response and Assessment System (INFFRAS) are some of the major initiatives to monitor the fire dynamics from local to global scales (Giriraj et al., 2010; Ahmad & Goparaju, 2017; Ray et al., 2021).

The impact of fires on plants, soil characteristics, and biomass has been the focus of several researchers over the past few decades (Whelan, 1995; Verma & Jayakumar, 2012). However, research on the effects of fire on the ecological dynamics of tropical deciduous forests is scarce in India (Saha, 2002; Verma & Jayakumar, 2015). Forest fires in tropical climate zones generally occur during the prolonged dry summer, when the mean ambient temperature is frequently higher than average (Gedalof et al., 2005), as is seen during the months of March to May in the tropical deciduous forest of Central India. Although plants in tropical dry deciduous forests exhibit some adaptable traits, such as thick bark, the capacity to heal fire scars, seed adaptations, and re-sprouting capability, which has been observed in the forest of the Central Indian region due to frequent fire incidences (Verma et al., 2017; Nolan et al., 2021). In the tropical dry deciduous forests of Central India, frequent forest fires, continuous fuelwood harvesting, and grazing had a substantial influence on tree diversity, density, dominance, regeneration, and a high rate of species endangerment (Kumar et al., 2022). Considering the increasing incidences of extreme fire events in the diversified Central Indian forests, the present study focused (a) to determine the forest fire susceptibility in terms of hot and cold spots coupling with contemporary (2000-2020) fire occurrences and also (b) to estimate its intensity and impacts on different vegetation types in the tropical deciduous forest of Central India to augment biodiversity conservation through appropriate fire management strategies.

2. Materials and Methods

2.1 Study Area

The present study was conducted in the Central Indian state of Madhya Pradesh (MP), located from 21°17′ to 26°52′ N latitude and 74°08′ to 82°49′ E longitude with a total area of 30.8 million sq. km (**Figure 1**) which equivalent to 9.38% of the country's total geographical area (FSI, 2019). Biogeographically, the state of MP can be classified into four zones, the low-lying areas in the north and north-west of Gwalior, the Malwa Plateau, Satpura, and the Vindhya ranges. The climate of Central India is subtropical with three distinct seasons: summer (March to May), winter (November to February), and the rainy season controlled by the southwest monsoon (June to October) (Guhathakurta et al., 2020). The cumulative annual rainfall ranges from 800 to 1,800 mm with higher rainfall (>1000mm) in the southern parts compared to extreme northern and southwestern parts (<800mm), while the temperature ranges between 22-25℃. The annual average frequency of dry days is higher (>280 days) in the northern and north-western parts as compared to eastern and south eastern parts (<250 days) and prominent during June months. The annual average frequency of rainy days in southeastern parts (>44 days) compared to northern and northwestern parts (<35 days) with highest during August while lowest during June months (Guhathakurta et al., 2020). The relief ranges from as low as 70 m in the north to high up to 1321 m in the south. The forest types in MP belong to five forest type groups, which are further divided into 21 forest types (Champion & Seth, 1968) (**Figure 2**). The dominant tree species are

T. grandis, S. robusta, Terminalia tomentosa, Butea monosperma, Diospyros melanoxylon, Lagerstroemia parviflora, Acacia catechu, Ziziphus xylopyrus, etc.

Insert figure 1 and 2 here

Figure 1. Study area map showing forest type along with the distribution of sampled transects affected with/ without forest fire in Central India

Figure 2. Area under different forest types and forest type group in Madhya Pradesh (as per FSI 2019)

2.2 Methodology

2.2.1 Forest fire mapping

The long-term forest fire occurrences based on MODIS active fire points were acquired from the Forest Survey of India (http://fsi.nic.in/forest-fire.php) for the period Nov. 2000 to Dec. 2020 (**Table 1)**. The SOI-based topographical sheets were used to demarcate forest cover and used to extract the fire points falling under the forest regions specifically. The mid-infrared and thermal infrared brightness temperatures of fires detected by the Terra and Aqua MODIS satellite channels are used as thresholds in a contextual algorithm that produces MODIS active fire data (Giglio et al., 2016). This active fire product is identified from fire data remotely sensed by satellites at a spatial resolution of 1 km pixels by rejecting false alarms to provide prediction with improved accuracy (Fornacca et al., 2017). Since their launch in 2000, the MODIS fire products have been used to contribute to the resolution of a wide range of scientific inquiries about the function of biomass burning in the Earth system (Chen et al., 2013, Chuvieco et al., 2008). The MODIS active fire points comprising geographic locations, dates, confidence levels, fire radiative power (FRP) (Lim et al., 2019), were acquired in shapefile format and used to generate the fire frequency map in the forest region by masking the non forest regions, and analyzed on a monthly and yearly basis during 2000-2020. The fire occurrences in each district of MP were analyzed in a geospatial environment. The LANDSAT 5 and Resourcesat LISS III based product of vegetation type map (2005) at 100m spatial resolution were acquired from NASA (https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1336; Roy et al., 2015) and used to spatially correlate with forest fire frequency to understand the susceptibility of fire frequency in varied forest types in MP, Central India.

Insert table 1 here

Table 1. Details of data used

2.2.2 Ground truthing and vegetation sampling

Phytosociological data had been collected from 218 (0.5 ha each) randomly selected locations of forest fire hotspot zones in MP during 2018 and 2019 (**Figure 1**). The mobile mapper (Spectra 50 Handheld GPS) was used for the identification of field sampling locations. Girth at breast height (GBH) at 1.37 m above the ground and height of all individual trees were recorded using the measuring tape and laser range finder (Nikon Forestry Pro), respectively. All the tree species were identified up to species level with the help of published literature, flora, and herbaria of the region. Various quantitative community characteristics had been determined following (Misra, 1968). Further, various vegetation indices including Shannon–Wiener diversity index (Magurran, 1988), Concentration of Dominance (Simpson, 1949), Evenness Index (Pielou, 1966), Margalef's index of species richness (Magurran, 1988), Menhinick's index of species richness (Whittaker, 1977) were calculated using standard formula as given in **Table 2** and have shown the detailed methodology flow chart in **Figure 3.** Besides, anthropogenic disturbance in terms of the availability of cut stumps in all the 218 field locations was studied and disturbance index (DI) was calculated following the formula given by Borah et al. (2014).

Insert table 2 and figure 3 here

Table 2. Details of vegetation indices used in the present study

Figure 3. Methodology flowchart

2.2.3 Hotspot Analysis

Getis-Ord Gi* algorithm (pronounced G-i-star) was used for fire hotspots analysis based on the spatial statistics hotspots analysis tool to measure the degree of association from a concentration of weighted points (Getis & Ord, 1992). The Getis-Ord local statistic is given by as:

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - \bar{X} \sum_{j=1}^{n} w_{i,j}}{S\sqrt{\frac{\left[n \sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2\right]}{n-1}}} \quad (1)$$

Where x_i is the attribute value for feature j, w_{ij} is spatial between feature I and j, n is equal; to the total number of features:

$$\bar{X} = \frac{\sum_{j=1}^{n} x_j}{n} \qquad (2)$$

$$S = \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - (\bar{X})^2} \qquad (3)$$

The Gi* statistics is a z- score so no further calculations are required. The Gi* statistics returned for each feature in the dataset is a z-score. For statistically significant positive z-scores, the larger the z-score is, the more intense the clustering of high hotspots. The Getis-Ord Gi* hotspot analysis has been used to demarcate the zones of forest fire hotspot and coldspot in the Central Indian deciduous forest of MP. Unlike Kernel Density, Getis-Ord Gi* hotspot analysis utilizes Gi* statistics to measure the degree of correlation of weighted features within the specified distance threshold (Getis and Ord, 1992; Songchitruksa and Zeng, 2010) based on the degree of clustering, randomness or fragmentation of a spatial pattern (Wubuli et al., 2015; Ord and Getis, 1995). Local statistics (*viz.*, Hot Spot Analysis through Getis-Ord Gi) assess each feature within the context of neighboring features and compare the local situation to the global situation (Anselin et al., 2010). In the present study, the MODIS active fire points were used to deduce forest fire hotspots and coldspots based on the incremental spatial autocorrelation that measures the degree of clustering of data in space at increasing distance (Rosenshein and scott, 2011). The high spatial correlation, either positive or negative (of Getis Ord G) highlights the unique feature of forest fire and is used to discriminate fire incidences from the surrounding land surface based on its occurrences over the years. All statistical analyses were performed using Microsoft Excel while the GIS analyses were carried out using ArcGIS *ver* 10.8.

3. Results

3.1 Forest fire incidents and their impact on forest types in Central India

The present study exhibited a total of 128540 fire incidents in the state of MP, Central India during 2000-2020. The study highlighted the high forest fire incidents in the recent decade (2011-2020) compared to the previous decade (2000- 2010) with an increasing growth of 27.11%. The trend line of forest fires incidents in Central India exhibited an overall increasing tendency of forest fire incidents with increasing trends in two only stable periods (2001-2003, and 2005-2007) during the initial decade in contrast to one dip/ stable period (2013-2015) during the later decade (**Figure 4a**). The high frequency of forest fire incidents was observed during March (40.5%) followed by April (38.1%), May (8.9%), and February (7.1%) (2000-2020) (**Figure 4b**).

Similar fire occurrences were observed in the Pachmarhi Biosphere reserve, which contributes 3.64% of the total annual forest fire of MP, with higher occurrences during April (44.50%), March (26.10%), and May (22.44%) (Figure 4c).

Insert figure 4 here

Figure 4. Fire incidents in Central India as mapped on (a) yearly basis, and (b) monthly basis, (c) with special reference to Pachmarhi biosphere reserve during 2000-2020

The pattern of two decades of MODIS satellite-based cumulative forest fire incidents (**Figure 5a**) exhibited very high fire incidents (>8000 forest fire incidents) in southern and central parts (East Nimar, Raisenand, Betul districts), followed by high fire incidents (>7000-8000 forest fire incidents) in northeastern parts (Panna district), moderate fire incidents (>5000-7000 forest fire incidents) in central and western parts (Damoh, Chhindwara, Balaghat, and Dewas districts), while low fire incidents (>2000-5000 forest fire incidents; 13 districts including Pachmarhi Biosphere Reserve), and very low fire incidents (<2000 forest fire incidents; 21 districts) in major parts of MP, Central India during 2000-2020 (**Figure 5b**).

Insert figure 5 here

Figure 5. (a) Yearly forest fire incidences in Central India, and (a1) PBR, (b) mapping of major fire prone districts based on forest fire incidents in Madhya Pradesh during 2000-2020

The forest type map exhibited the dominance of deciduous broadleaf forest (65.2% of the total forested area) followed by shrubland (14.7%), deciduous needleleaf forest (10.3%), mixed forest (9.7%), plantation and grassland (<0.2%) in Central India (**Figure 1**). The impact of forest fires' on different vegetation types exhibited the recurrence of fire incidences and its substantial affected on deciduous broadleaf forest (affecting 31.56% of select forest types), followed by deciduous needleleaf forest (30.23%), shrubland (7.52%), mixed forest (9.80%), while negligible fire incidences were observed in plantation and grassland (**Figure 6a-b**). On the other hand, with reference to vegetation type the majority of forest fires incidents occurred in the tropical dry deciduous forests (88.65%) followed by tropical moist deciduous forests (8.97%), and tropical thorn forests (0.26%).

Insert figure 6 here

Figure 6. (a) Fire incidences in major vegetation types in Central India, and (a1) in PBR, (b) graphical representation of forest fire frequency over varies forest type in the Central India

3.2 Forest Fire Hotspots Analysis

The spatio-temporal patterns of forest fires-based hotspots using Gi-Bin optimized hotspot analysis demonstrated that the areas of frequent fire incidents with very high-density forest fire hotspots (99% confidence) were observed in the southern parts of the entire Vindhya mountain ranges elongated from western to eastern direction and in Satpura range. while the peripheral areas of the regions were identified as high-density forest fire hotspots (90-95% confidence) in Central India during 2000-2020 **(Figure 7a)**. These high and very high-density forest fire hotspots comprise ~24.6% of forested grids of MP state and were a recurrent influence of forest fire over the decades. It has impacted largely on deciduous broadleaf forest (77.44% of total forest fire hotspot), followed by shrubland (9.29%), mixed forest (7.08%), and deciduous needleleaf forest (6.17%). In contrast, the forests in the northern, eastern, and western parts comprising 33.7% of forested grids were attributed as a very high-density cold spot (90-99% confidence) with negligible forest fire incidents over the two decades. Cold spot was largely observed in a deciduous broadleaf forest (73.64% of total forest fire coldspot), followed by mixed forest (13.89%), shrubland (11.16%), and deciduous needleleaf forest (1.27%). Moreover, the dominance of non-significant forest fire hotspots (comprising 41.7% of forested grids) observed in a large proportion of the forests primarily in south-eastern, eastern, and northern parts exhibited no severe impacts of forest fire and related with deciduous broadleaf forest (65.39%) and deciduous needleleaf forest (22.32%). A Moran's Index of 1.19 was calculated with a Z score of 9.85. The Z score indicated that the pattern observed was not random ($p<0.01$) but clustered **(Figure 7b)**. The present study provides essential insights into the delineation of fire-prone vegetation types and their dominance in MP that will help in determining the impacts of forest fires on forest productivity and also help in improving the fire management strategies.

Insert figure 7 here

Figure 7. (a) Forest fire hotspots based on Gi-Bin optimized hotspots analysis (b) Gi-Bin spatial autocorrelation report in the state of Madhya Pradesh, Central India

3.3 Phytosociological characteristics of fire-impacted tropical deciduous forests of Central India

The phytosociological information acquired for the period 2018-2019 in 218 randomly selected ground points within the fire hotspots zone by laying a belt transect of 125 m x 40 m (0.50 ha) size in each point covering a total of 109 ha forest area in tropical dry deciduous mixed forests of MP, Central India. A total of 106 tree species belonging to 34 families and 79 genera were recorded in the present study (**Table 3**).

Insert table 3 here

Table 3. Community characteristics of the 218 field locations of fire-impacted tropical dry deciduous forests of Madhya Pradesh, Central India

Fabaceae was the most dominant family with 25 spp. followed by Rubiaceae and Combretaceae, with 7 spp. each, Bignoniaceae with 6 spp., Celastraceae, Malvaceae, Moraceae with 5 spp. each, 05 families with 03 spp. each, 09 families with 02 spp. and the other 25 families were monotypic. In our study, a total of 24877 individuals of adult trees (GBH: >30 cm) were recorded across the 218 sampled locations of tropical deciduous forests of MP, with a total tree density of 228 ind. ha^{-1} and dominance of 8.76 m^2 ha^{-1}. While the diversity index (Shannon H') was low (2.90), the evenness index was moderate (0.62) signifying poor species diversity with the dominance of few selected species in the fire impacted field locations. Out of the total 106 tree species, 06 species were highly fire-resistant, found in more than 50% of the fire hotspots regions *viz*., *Tectona grandis* L.f. (98% fire hotspots), *Butea monosperma* (Lam.) Taubert (66%), *Diospyros melanoxylon* Roxb. (65%), *Lagerstroemia parviflora* Roxb. (63%), *Lannea coromandelica* (Houtt.) Merr. (54%), and *Terminalia anogeissiana* Gere & Boatwr. (53%).

The tree density in the 218 fire hotspot zones ranged from 52 to 644 (ind. ha^{-1}) with a mean of 228 ± 6.20 SE, while dominance ranged from 0.95 to 2.38 m^2 ha^{-1} (mean 8.52 ± 0.25 SE). Similarly, the Shannon-Weiner diversity index (H') ranged from 0.22 to 2.76 (mean: 1.68 ± 0.03) and the evenness index ranged from 0.25 to 0.91 (mean: 0.76 ± 0.006 SE) (**Table 4**).

Insert table 4 here

Table 4: Detailed phytosociological characteristics of 218 field locations of fire-impacted tropical dry deciduous forests of Madhya Pradesh, Central India

Out of the total 218 field locations, 39 (18%) locations had low density (52-150 ind. ha^{-1}), 160 (73%) locations had moderate density (150-350 ind. ha^{-1}), and 19 (9%) locations had only high density (>350 ind. ha^{-1}). Similarly, 118 (54%) locations had low tree species richness (01-09 spp.), 95 (44%) had moderate tree species richness (10-18 spp.), and only 05 (2%) locations had high tree species richness (>18 spp.). Out of the total 218 fire-impacted field locations, 157 locations (72%) were highly disturbed by anthropogenic disturbances in terms of the availability of cut stumps as out of the total 24877 individuals of tree species recorded from the 218 field locations, 1609 (6.47%) were cut stumps recorded from 157 field locations. The disturbance index of the 218 field locations was 5.02% in terms of the basal cover. Besides, occasional to recurrent livestock grazing (96.33%), fuelwood collection (52.29%), forage removal (45.87%), and NTFPs collection (18.35%) were also recorded during the field sampling during various seasons.

4. Discussion

Forest fires have become a global threat because of the elongated fire seasons brought on by a warmer climate (Jolly et al., 2015). Annually, ~3.73 Mha of forest areas in India experience forest fires, the majority of which (90%) are caused by human activity (Srivastava & Garg, 2013). The present study elucidated the occurrence of major forest fire incidents in the months of March (40.5% of total incidents) followed by April (38.1%), May (8.9%), and February (7.1%) during 2000-2020, which are highly correlated with climate severity (Ahmad & Goparaju, 2017). In addition, the high fire frequency during specific months are primarily attributed to meteorological (lightning), climatic, and anthropogenic disturbances (Myers & Rodríguez-Trejo, 2009) that regulates fire intensity, spread, and behavior (Westerling et al., 2006). The recurrence of very high to high fire incidents and forest fire hotspots in southern, central, northeastern parts of MP state substantially affected deciduous broadleaf forest (affecting 31.56% of select forest types), deciduous needleleaf forest (30.23%), and shrubland (7.52%) (**Figure 7a-b**). Tropical dry deciduous forests are more vulnerable to forest fire due to the impacts of seasonality and dominance of deciduous tree species with poor ground cover compared to other forests around the globe (Janzen, 1988) and in India (FSI, 2019). Similar geographical linkages have been reported by previous studies (Ahmad et al., 2018; FAO and UNEP, 2020). The high forest fire incidents in Central India primarily affected the selected parts of MP, largely characterized by deciduous broadleaf forest (65.2% total area) and deciduous needleleaf forests (10.3%) with dominance of tribal communities, whose dependence on forests for sustenance needs are quite high. Local tribes burn the ground vegetation to aid in the collection of mahua flowers (*M. longifolia*) to brew alcoholic beverages as it is easier to find the fallen small cream-colored flowers when there is no undergrowth (Kumar & Saikia, 2020). Local alcoholic beverage preparation is a very common means of economic sustainability among the tribals and in the present study *M. longifolia* was prevalent in 23.39% transects. Anthropogenic fire to initiate the new leaves and sprouts to collect the *tendu* leaves (*Diospyros melanoxylon*) to make wrapping papers for beedi (local cigarettes), or to maintain open canopy cover and space for bodha grass (*Cymbopogon nardus*) to use in thatching (Schmerbeck & Fiener, 2015), and in other majority of grasses to use as forage for livestocks may be the reason of higher dominance of fire hotspots in the tribal dominating areas located in the southern, central, northeastern parts of the studied forests. *Tendu* leaf collection was the second most important cause of fire in Chhattisgarh, Jharkhand, MP, and Telangana after the Mahua flower collection (MoEFCC & World Bank, 2018; Kumar & Saikia, 2020). Other NTFPs harvested with the aid of fire include fodder, honey, mushrooms, seeds, medicinal plants, charcoal, bamboo shoots, vegetables, fruits, tubers, and dammar gum or resin (MoEFCC & World Bank, 2018). Forests that are affected by fire may also be affected by agricultural activities, livestock grazing, harvesting of fuelwoods and other non-timber forest products (NTFPs), encroachment or fragmentation for road construction, illicit felling, and invasive species (Kumar & Saikia, 2020). In the present study, most of the forest patches are also disturbed in terms of timber felling (72% transects), livestock grazing (96.33%), forage removal (45.87%), fuelwood collection (52.29%), and NTFPs collection (18.35%). The states of Chhattisgarh, Jharkhand, MP, Odisha, and Telangana are the most responsible Indian states for causing human-induced forest fires basically for obtaining NTFPs (MoEFCC & World Bank, 2018). In contrast, the forests in the northern, eastern, and western parts are identified as major cold spots due to least or negligible incidents of forest fire over the two decades (Satendra & Kaushik, 2014).

Forest fire's impact on species composition is significant as it affects forest regeneration, growth, and development, including flowering, fruiting, seed dispersal, germination, and seedling establishment (Danthu et al., 2003; De Luis et al., 2005). The climatic variability including precipitation, relative humidity, temperature, and wind speed coupled with the slope and gradient of the landscape influence the spreading of fumes, by increasing the fire ignition (Littell et al., 2016). The latitudinal and altitudinal gradient in the Central Indian tropical deciduous forest, influence the temperatures, relative humidity, and precipitation patterns, which further drive forest fires (Adab et al., 2013; Matin et al., 2017). The lower elevation zones (300-600m) are more prone to high forest fire hotspots in contrast to the moderate (600-800m) and high elevation zones as observed in Central India (**Figure 6a**). Apart from the natural factors, human-induced climate change is an important determinant of forest fire, which is evident across the world, including Central India, Canada, USA, UK, and many other European countries (Kirchmeier-Young et al., 2019). The local climate, soil conditions, historical legacies, and extreme events, together with biophysical feedback, can induce a massive shift in ecosystem composition in response to a single fire event, determining the resilience or vulnerability of forest species composition to changing fire regimes (Iglesias & Whitlock, 2020). Precipitation variability, the probability of extreme dry and wet events, long-term warming, and increasing atmospheric water deficits all contribute to increased physiological and hydrological stress and forest flammability as a result of climate change (Malhi et al., 2020). Despite the fact that climate change has a moderate impact on ecosystem compositions than direct anthropogenic interventions, the negative ecological consequences of climate change are becoming increasingly apparent and are predicted to intensify in the future decades (Mair et al., 2014; Ohashi et al., 2019).

Forest fires can be either beneficial or harmful depending on their intensity, return interval, and impacts (Verma & Jayakumar, 2012), while it plays a complex role in the tropical dry deciduous forests as fire felicitates the natural regeneration in a few of the important tree species including *T. grandis* and *S. robusta* in dry deciduous forests in India. In contrast, repeated fires incidents of short intervals are having a more disruptive effect on forest composition, structure, and species diversity as reported in several other studies in Central and Southern India (Kodandapani et al., 2008). The present study reported 106 tree species in 218 forest fire hotspots locations with a total tree density of 228 ind. ha^{-1} and dominance of 8.76 m^2 ha^{-1}. While, a very less tree species richness (10 spp.) with a comparable total tree density of 255 ind. ha^{-1} and slightly high dominance (10.11 m^2 ha^{-1}) were reported in high fire zones in tropical deciduous forests of Bhoramdeo Wildlife Sanctuary, Chhattisgarh (Jhariya et al., 2014) and are primarily driven by latitudinal gradients (Liang et al., 2022). Altered species composition, diversity, and reduced seedling density were also been reported in areas of dry deciduous forest with the shortest fire return intervals compared to forest patches with lower fire frequency in the moist deciduous forests of Nilgiri Biosphere Reserve, Western Ghats (Kodandapani et al., 2009). On the contrary, there was no difference in survival rates of juvenile tree species in both burnt and unburnt areas, even for plots affected by multiple fires over a short period (Mondal & Sukumar, 2015). Adaptive characteristics are observed in tropical dry deciduous forests, where fires are frequent including strong bark, the capacity to repair fire scars, seed adaptations, and the ability to resprout (Khan & Tripathi, 1986). Few fire-tolerant species can replace the naturally occurring species in a disturbed area because of recurrent fires' influence. The present study recorded *T. grandis* as the most fire-resistant tree species recorded in 98% of fire hotspots followed by *B. monosperma* (66%), *D. melanoxylon* (65%), *L. parviflora* (63%), *L. coromandelica* (54%), and *T. anogeissiana* (53%). The study suggests the replacement or non-existence of such more fire-resistant tree species may induce much larger impacts and necessitate planting such tree species and more resilient native and adaptive tree species to counter the increasing forest fire impacts at a large scale.

The relationships between tree density, dominance, diversity, and evenness in documented forest fire hotspot zones impacted tropical dry deciduous forests of MP, Central India. The tropical dry deciduous forests of Central India are dominated by low (<250 ind. ha^{-1}; 65% of 218 studied forest fire hotspots) to moderate density (250-400 ind. ha^{-1}; 30%), together with low (<10 m^2 ha^{-1}; 72%) to moderate dominance (10-15 m^2 ha^{-1}; 21%), **(Figure 8a-b)**. Similarly, the fire-affected forests of Central India recorded low (<1.50; 35%), moderate (1.50- 2.00; 39%), to high diversity (H') (>2.00; 25%) together with high (>0.75; 63%) to moderate species evenness (0.50-0.75; 35%) **(Figure 8c-d).** Previously, a comparatively higher tree density (ranged 516 to 3412 Ind. ha^{-1}) were reported from parts of MP enumerated from 39 preservation plots (Singh et al., 2021), while low tree density (21 to 228 ind. ha^{-1}) and high diversity (H'=3.22) were reported from the tropical deciduous forest of Satpura forest from 73 documented grids (Lal et al., 2021). A comparable tree density (349-1875 (Ind. ha^{-1}) was recorded from tropical dry deciduous forests of Central India (Chaturvedi et al., 2011; Joshi & Dhyani, 2019), and the tropical forests of Mexico (Duran et al., 2006). The ecological impacts of forest fires are specific to the different types of forests, situated in different climates zones and subject to other anthropogenic disturbances (Satendra & Kaushik, 2014). The ability of forests to withstand and recover from fires depends largely on the management of other anthropogenic and natural disturbances (MoEFCC & World Bank, 2018).

Insert figure 8 here

Figure 8. (a) Density, (b) dominance, (c) Shannon Wiener's diversity index, and (d) species evenness in the forest fire hotspots zones in Central India

5. Conclusions

The current research focused on long-term forest fire incidences at seasonal, monthly scales and fire hotspots in different forest types of Central India. The study concluded higher incidences of forest fire in the recent decades (2010-2020: 55.91%) in Central India compared to the previous (2000-2010: 44.09%). The MODIS based daily forest fire analysis two decades exhibited a large occurrence of fire over the deciduous broadleaf forest (82.3% of total fire incidences) followed by deciduous needleleaf forest (11.9%), shrubland (3.0%), mixed forest (2.7%), and negligible fire incidences on plantation and grassland. The forest fire hotspots regions have comparatively lease tree density (228 ind. ha^{-1}) and low dominance (8.76 m^2 ha^{-1}). The forests in eastern, western, and central parts of MP have been observed as high forest fire hotspots while forests in the northern, eastern, and western parts are identified as major cold spots with the least risk of forest fire occurrences. The present study recorded *T. grandis* as the most fire-resistant tree species recorded in 98% of fire hotspots followed by *B. monosperma* (66%), *D. melanoxylon* (65%), *L. parviflora* (63%), *L. coromandelica* (54%), and *T. anogeissiana* (53%). The hotspot's statistical modeling would greatly contribute to biodiversity conservation through proper management of forest fires during the peak periods of wildfire in the State of MP. The study elucidated the high susceptibility of forest fire in deciduous forests in Central India and necessitated proper management of forest fires by encouraging fire-resistant species, and prioritization of regions under fire hazards through the adoption of preparedness and response strategies to minimize the forest fire impacts.

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Table 1. Details of data used

Data type	Details	Source
Fire Occurrence data	MODIS Active (MCD 14DL) Fire data 1km resolution (2000-2020).	(http://fsi.nic.in/forest-fire.php); https://firms.modaps.eosdis.nasa.gov/
Forest cover	Forest cover boundary based on SOI topographical sheet (1:50,000)	Survey of India (SOI)
Vegetation type Map	LISS 4-5 and ETM+, LISS-III with 100 m resolution	https://daac.ornl.gov/VEGETATION/guides/Decadal_LULC_India.html
Phytosociological data	218 randomly sampled transects of 0.50 ha size	Field survey during 2018-2019.

Table 2. Details of vegetation indices used in the present study

Vegetation Indices	Formula	Reference
Importance Value Index (IVI)	$IVI = RD + RF + RDm$	Phillips, 1959
Margalef's species richness Index (Dmg)	$Dmg = \frac{(S-1)}{ln\ N}$	Magurran, 1988
Menhinick's species richness Index (Dmn)	$Dmn = S\sqrt{N}$	Whittaker, 1977
Shannon–Wiener Diversity Index (H)	$H' = -\sum_{i=1}^{s} pi \ln pi$	Shannon and Wiener, 1963
Concentration of dominance (CD)	$CD = \sum_{i=1}^{s} (pi)^2$	Simpson, 1949
Pielou's Evenness Index (E)	$E = \frac{H'}{Hmax}$	Pielou, 1996
Effective number of species (ENS)	$ENS = Exp(H')$	MacArthur, 1965
Disturbance index (DI)	$DI(\%) = \frac{Basal\ area\ of\ cut\ stumps}{Total\ basal\ area} \times 100$	Borah et al., 2014

Table 3. Community characteristics of the 218 field locations of fire-impacted tropical dry deciduous forests of Madhya Pradesh, Central India

Total tree density (Ind. ha^{-1})	228
Dominance (m^2 ha^{-1})	8.76
Shannon-Weiner Diversity Index (H')	2.90
Concentration of Dominance (CD)	0.14
Evenness Index (EI)	0.62
Margalef's index of species richness (Dmg)	10.37
Menhinick's index of species richness (Dmn)	0.67
Effective Number of Species (ENS)	18
Disturbance Index (DI) (%)	5.02
Tree species richness (No.)	106
Genera (No.)	79
Families (No.)	34
Most dominant family	Fabaceae (25 spp.)
Most dominant genus	*Terminalia* (07 spp.)
Most dominant tree species	*Tectona grandis* L.f. (111 ind. ha^{-1})

Table 4: Detailed phytosociological characteristics of 218 field locations of fire-impacted tropical dry deciduous forests of Madhya Pradesh, Central India

Community characteristics	Mean	Standard Error	Minimum	Maximum
Tree species richness	10	0.28	01	23
Density (Ind. ha^{-1})	228	6.2	52	644
Dominance (m^2 ha^{-1})	8.52	0.26	0.95	20.38
Shannon-Weiner Diversity Index (H')	1.68	0.03	0.22	2.76
Concentration of Dominance (CD)	0.33	0.01	0.04	1.0
Evenness index (EI)	0.77	0.006	0.25	0.91
Dmg	1.83	0.056	0.20	4.16
Dmn	0.91	0.024	0.03	1.86
ENS	5.96	0.018	1.24	15.74

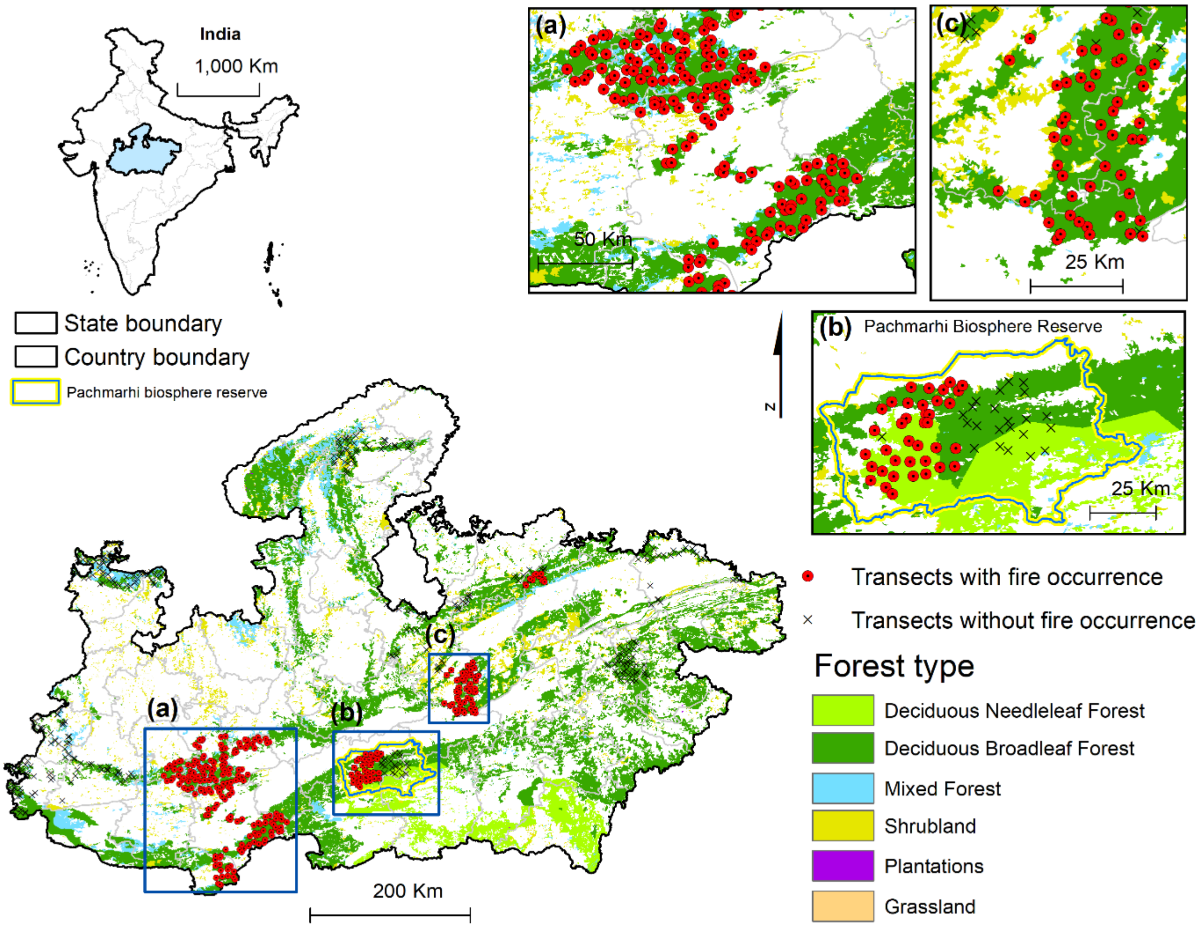


Figure 1. Study area map showing forest type along with, the distribution of sampled transect affected with forest fire in Central India

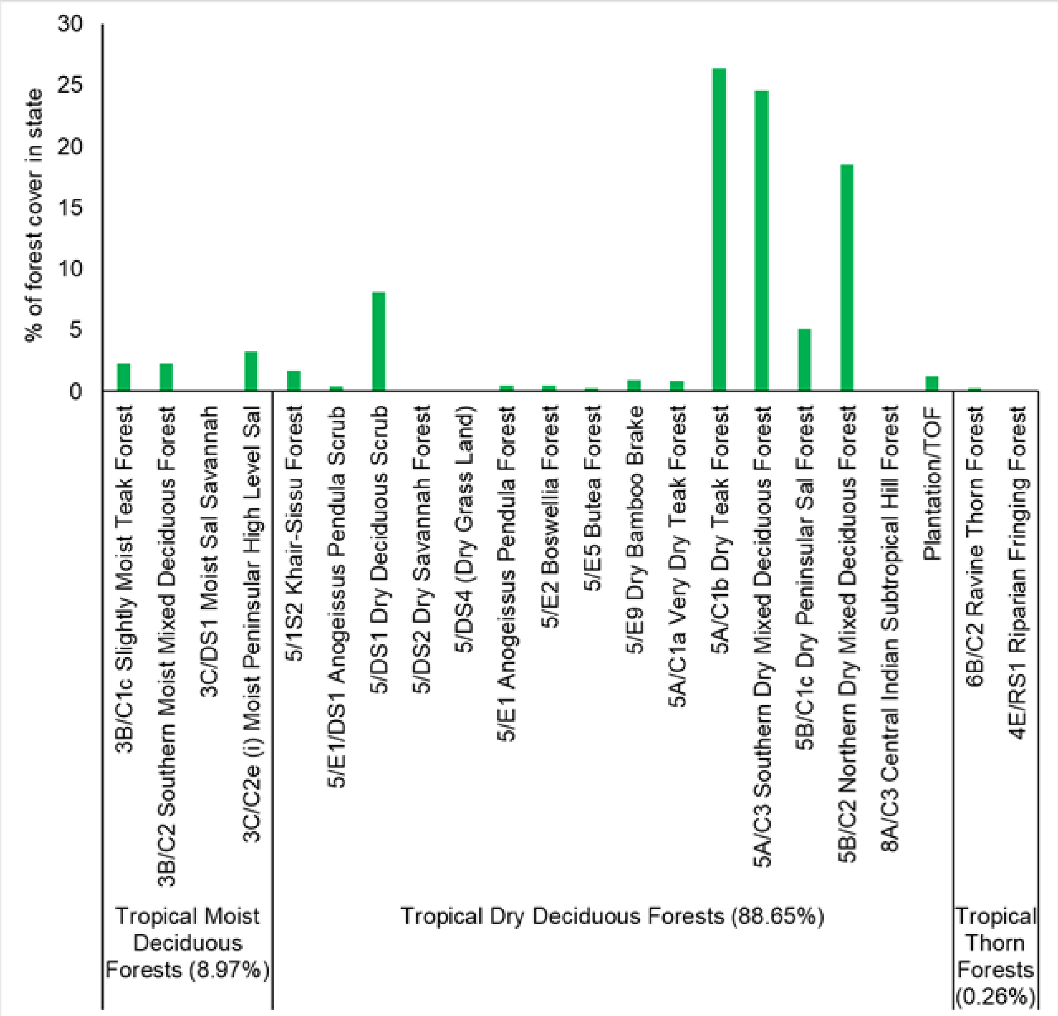


Figure 2. Area under different forest types and forest type group in Madhya Pradesh (as per FSI 2019)

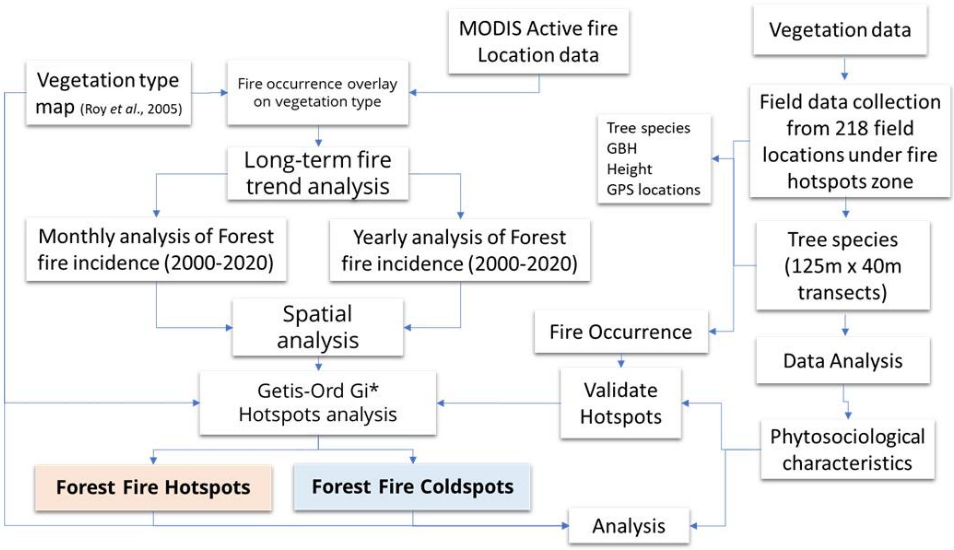
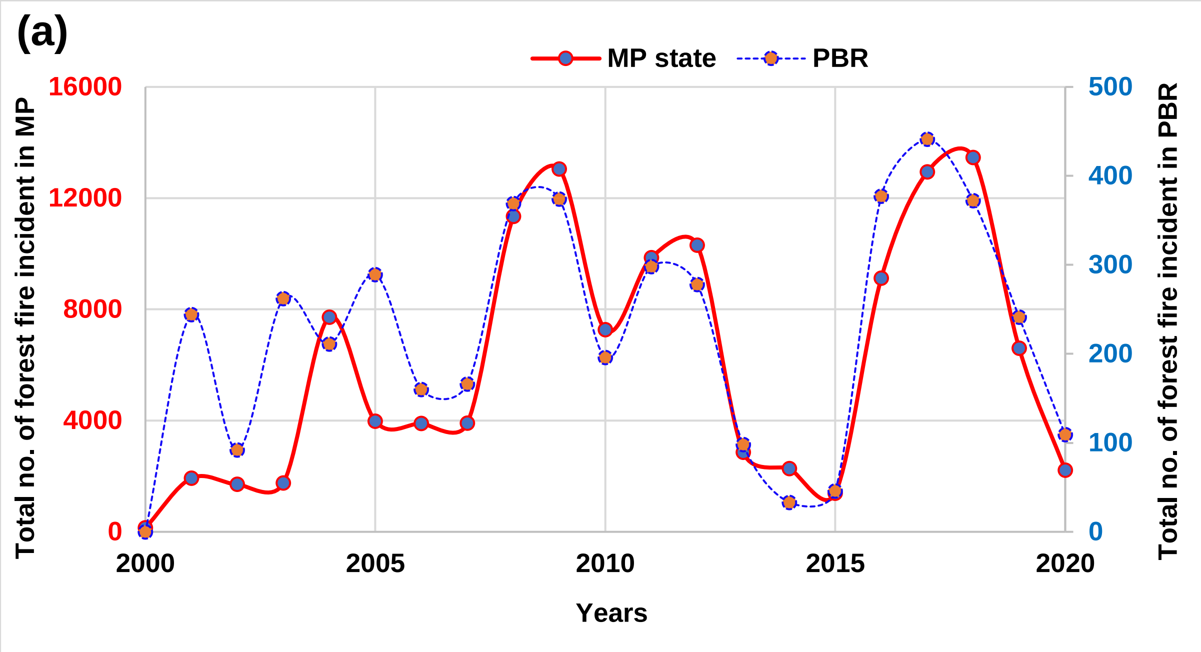


Figure 3. Flowchart showing the detailed methodology



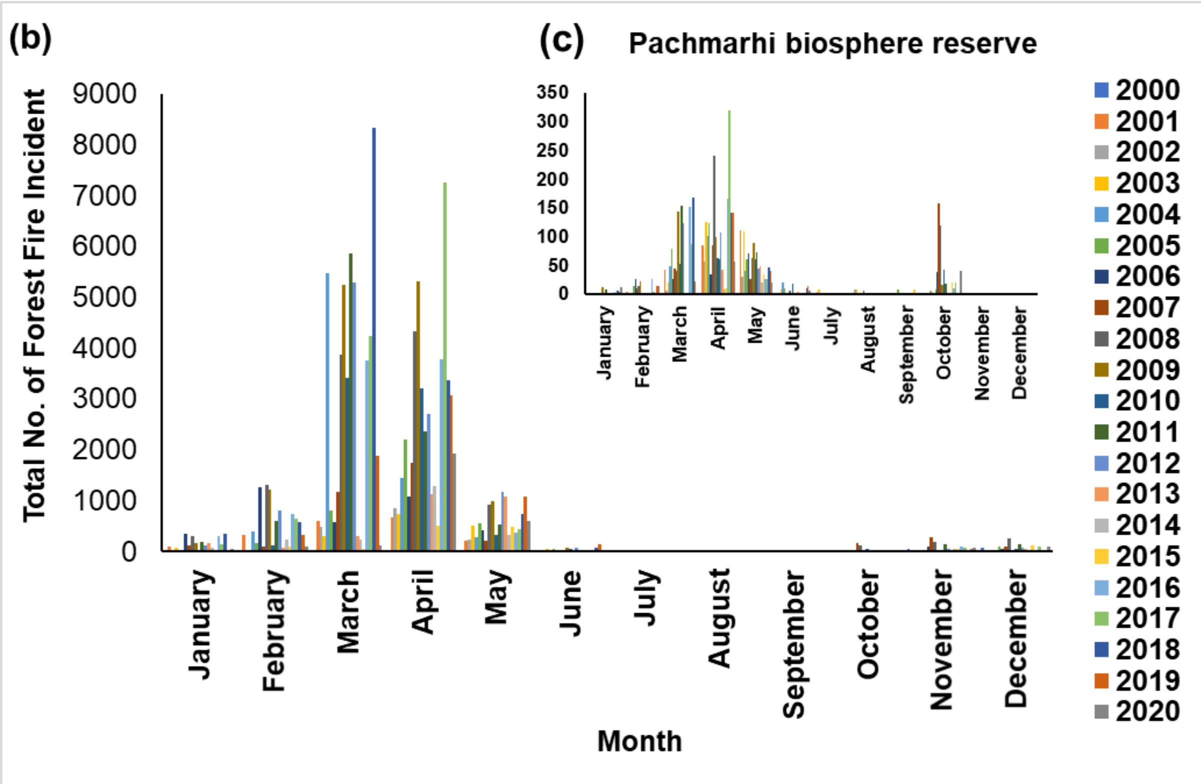


Figure 4. Fire incidents in Central India as mapped on (a) yearly basis, and (b) monthly basis, (c) with special reference to Pachmarhi biosphere reserve during 2000-2020

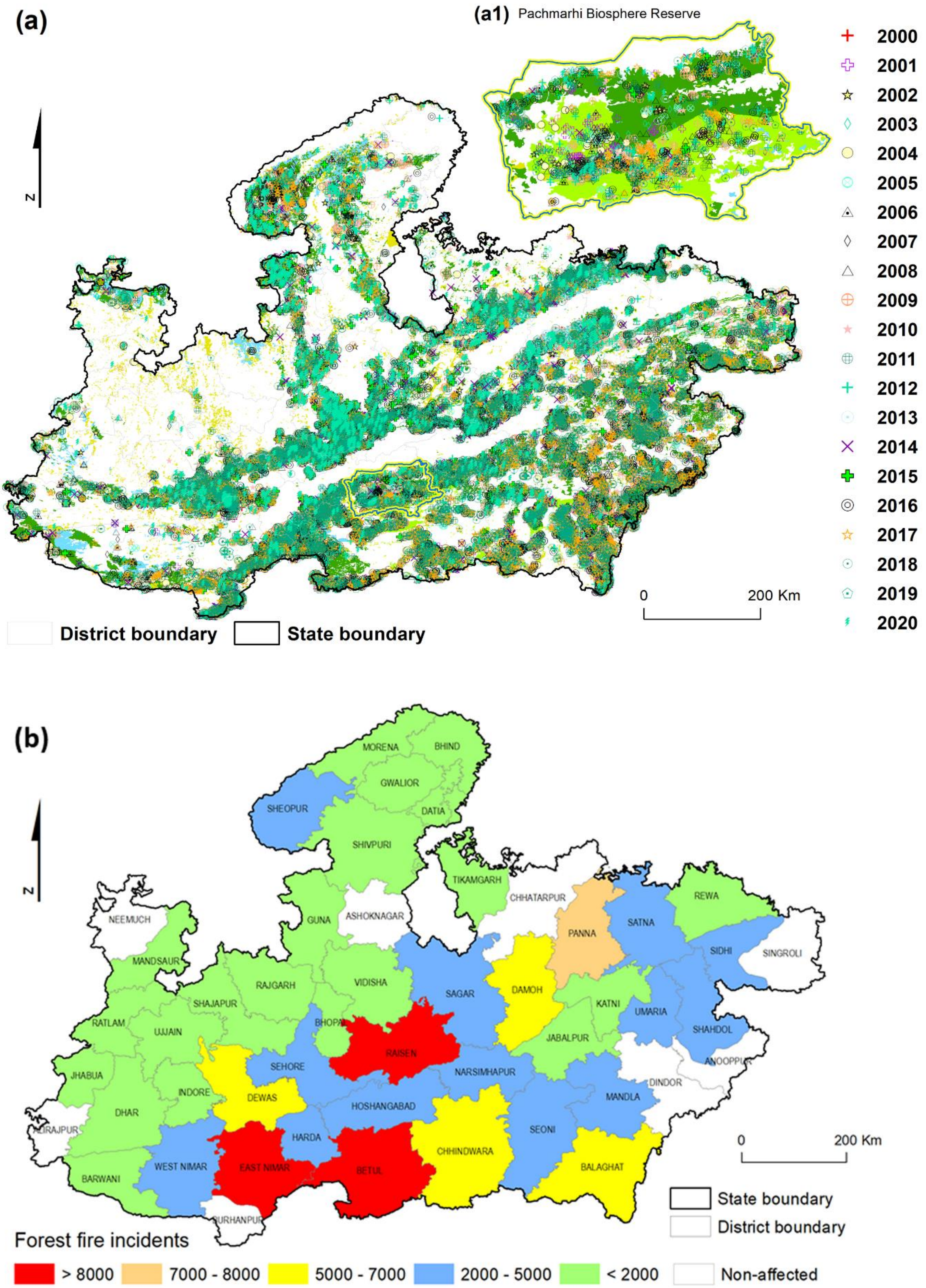


Figure 5. (a) Yearly forest fire incidences in Central India, and (a1) PBR, (b) mapping of major fire prone districts based on forest fire incidents in Madhya Pradesh during 2000-2020

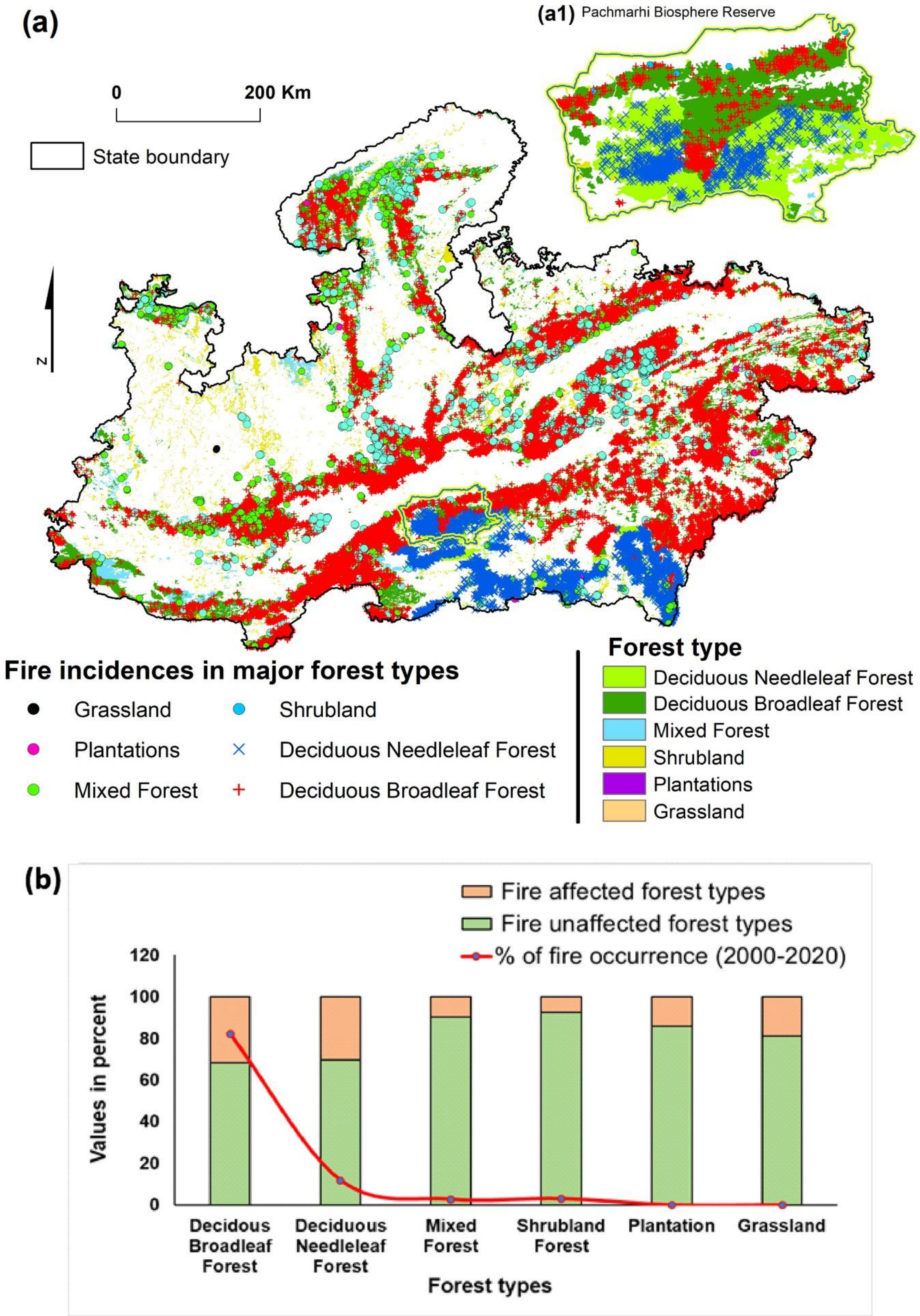


Figure 6. (a) Fire incidences in major vegetation types in Central India, and (a1) in PBR, (b) graphical representation of forest fire frequency over varies forest type in the Central India

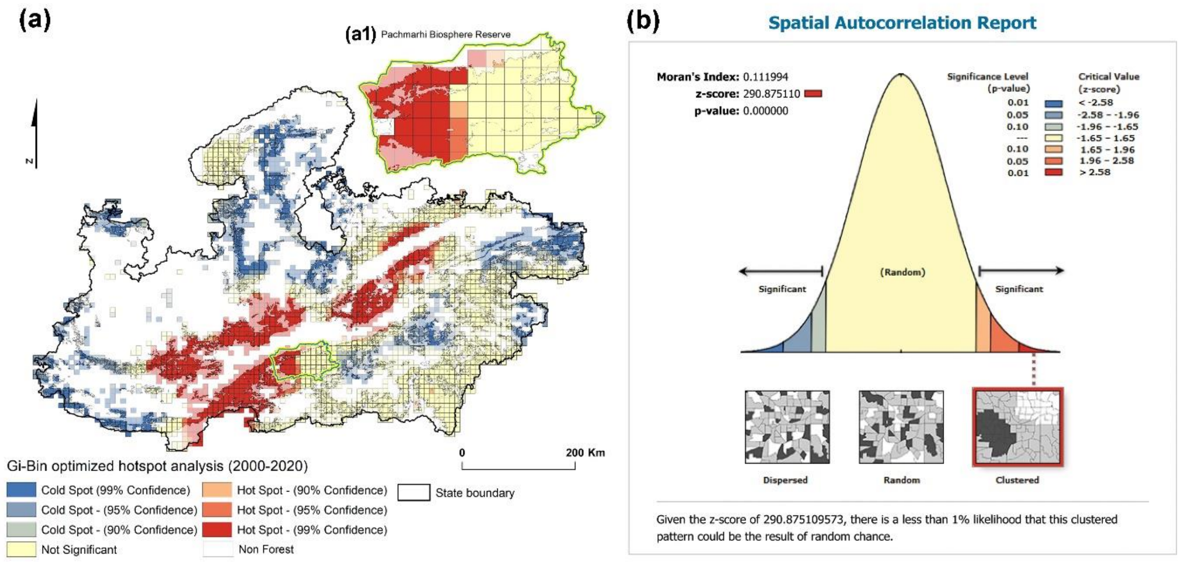


Figure 7. (a) Forest fire hotspots based on Gi-Bin optimized hotspots analysis, and (a1) PBR (b) Gi-Bin spatial autocorrelation report in the state of Madhya Pradesh, Central India

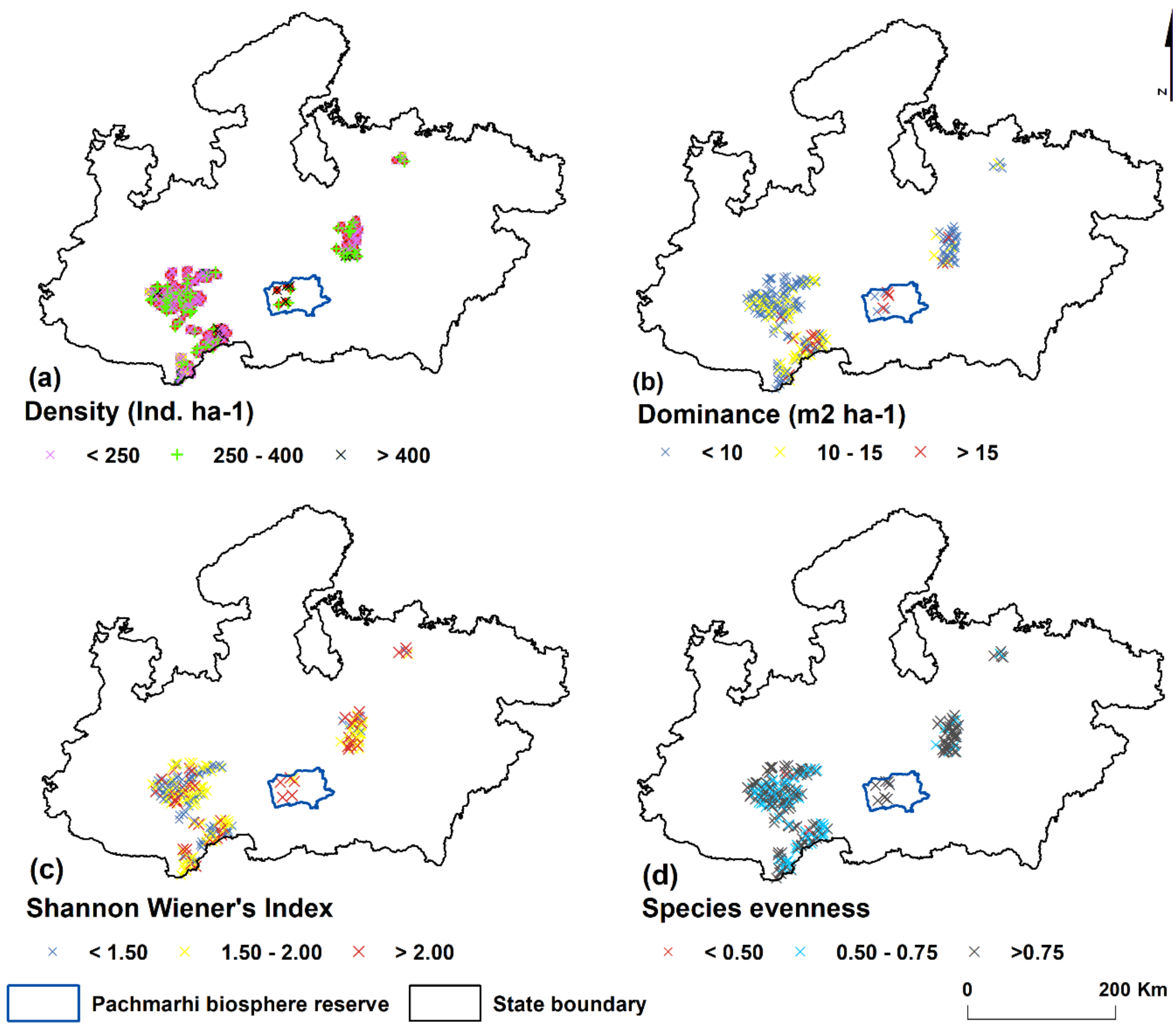


Figure 8. (a) Density, (b) dominance, (c) Shannon Wiener's diversity index, and (d) species evenness in the forest fire hotspots zones in Central India