

# Evaluation of Forest Fire Anomalies with Novel Metrics and Management Effectiveness: Evidence from 14 Central Indian Tiger Reserves

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## Method Article

**Keywords:** Forest Fire Assessment Metrics, Forest Flammability Index, Management Effectiveness, Central Indian Tiger Reserves

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# **Evaluation of Forest Fire Anomalies with Normalised Metrics and Management Effectiveness: Evidence from 14 Central Indian Tiger Reserves**

## **Abstract**

Traditional forest fire assessments primarily rely on fire occurrence and burned area, which quantify the magnitude of fire activity but do not explicitly account for differences in reserve size, proportional fire impact, vegetation flammability, or management effectiveness. This study evaluates three complementary normalized fire metrics—Fire Occurrence Density (FOD), Burned Area Proportion (BAP), and Burned Area per Fire Occurrence (BAFO)—across 14 Central Indian Tiger Reserves (TRs) using MODIS-derived active fire and burned area datasets (2001–2022). While these metrics are mathematically derived from conventional fire occurrence and burned area, they provide complementary descriptors of fire activity by representing fire occurrence density, the proportion of reserve area affected by fire, and the average burned area associated with each active fire detection. Their relationships with Forest Flammability Index (FFI) and Management Effectiveness Evaluation (MEE) scores were subsequently examined using correlation analysis. The results indicate that BAP and BAFO exhibited stronger associations with FFI and MEE than fire occurrence alone, while also distinguishing TRs with similar conventional fire metrics but contrasting normalized fire characteristics. Integrating normalized fire metrics with FFI and MEE provides a comprehensive framework for comparative forest fire assessment across protected areas and may support conservation planning and management prioritization.

**Keywords:** Forest Fire Assessment Metrics, Forest Flammability Index, Management Effectiveness, Central Indian Tiger Reserves

## 25    **1.     Introduction**

26   Forest fires have emerged as a major global environmental hazard, causing significant  
27   ecological degradation, biodiversity loss, and socioeconomic impacts (Meng et al. 2023, Arif  
28   et al. 2021; Tyukavina et al. 2022). Also, it significantly contributes to global warming and  
29   environmental degradation, releasing 1.6–10 billion tons of CO<sub>2</sub> annually and causing an  
30   estimated 260–600 thousand premature deaths worldwide, making it a major contributor of  
31   climate change (FSI, 2021, Nesha et al. 2021, Kumar et al. 2025). Globally, approximately  
32   38% forest loss is attributed to forest fires (Van Wees et al. 2021). In India, increasing fire  
33   frequency has resulted in approximately 36% of forests being classified as fire-prone (FSI,  
34   2021). Fire dynamics and burned area modelling over India also show concerning trends across  
35   central India (Bar et al. 2024; Jain et al. 2021; Gorain et al. 2025).

36   The Central Indian & Eastern Ghat landscape hosts nearly half of India's tiger reserves (TRs)  
37   (Yadav et al. 2023), along with numerous other ecologically sensitive protected areas. This  
38   region is a global priority landscape for tiger conservation, with the strongest wildlife linkage  
39   for animal movement in Central India (Dutta et al. 2016). It hosts moist to dry deciduous forest  
40   types and varied terrain, from valleys to hills, supporting rich biodiversity (Qureshi et al. 2023).  
41   Satpura Tiger Reserve, which consists of such climate, demonstrates occurrences are strongly  
42   influenced by climatic factors and anthropogenic activities (Ray et al. 2023; Niyogi et al. 2025;  
43   Tamrakar et al. 2024). However, despite these risks, the threat of forest fires to TRs remains  
44   insufficiently assessed, highlighting a critical evaluation and methodological gaps that the  
45   present study aims to address.

46   Previous forest fire assessments have predominantly relied on conventional metrics such as fire  
47   occurrence and burned area (Niyogi et al. 2025; Jain et al. 2021; Mani and Varghese 2021; Pati

et al. 2024; Xiang et al, 2023; Archibald et al., 2013; Ahmad and Goparaju 2019; Giglio et al., 2018). While these metrics effectively quantify the magnitude of fire activity, they are not normalized for reserve size and may therefore hinder meaningful comparison among TRs of substantially different geographical extents. It has been also noted that a relatively small number of fires accounts for the majority of burned area, with the largest 1% of fires contributing 80–96% of total damage (Strauss et al., 1989). It is reported that, apart from natural causes, largely obscure illegal anthropogenic activities dominate fire incidences in the central India (Tamrakar et al. 2024, Jain et al. 2021). Additionally, isolated fire frequency and/or burned area-based investigation often ignore critical aspects such as the average size of individual fires, and the interactions between fire behaviour, forest type, and management practices. Consequently, there is a need for more robust and integrated fire indices that combine information on fire occurrence and burned area to better characterize fire regime and spatial patterns of fire disturbance across landscapes (Archibald et al., 2013; Andela et al., 2017; Smith et al., 2020).

Another key drivers of forest fire spread are fuel load and its flammability (Dimitrakopoulos, 2001). The term “flammability” has no strict and clear definition, which is often used to indicate the ability of a given fuel to ignite and support fire (Mak, 1988; Hogenbirk & Sarrazin-Delay, 1995; Pellizzaro et al., 2007). Existing fire assessment studies largely overlook the quantification of flammability, despite its potential role as a relative driver of fire regimes (Kale et al.2017; Kale et al., 2024).

Therefore, we adopt a data-driven approach using remote sensing–derived land use–land cover data, by quantifying the relative contribution of different forest types to historical burned areas. Finally, in protected areas such as TRs, which are managed through conservation interventions,

management effectiveness (Mathur et al. 2017; Yadav et al. 2022) can also be considered in forest fire assessments.

Despite the widespread use of fire occurrence and burned area for forest fire assessment, standardized descriptors that enable meaningful comparison among Tiger Reserves (TRs) of substantially different geographical extents remain limited. Moreover, the extent to which normalized fire metrics can complement conventional fire metrics in relation to forest flammability and management effectiveness has received limited attention. Accordingly, the objectives of this study are to: (i) develop and apply three normalized fire metrics—Fire Occurrence Density (FOD), Burned Area Proportion (BAP), and Burned Area per Fire Occurrence (BAFO); (ii) evaluate their ability to provide standardized comparison among 14 Central Indian Tiger Reserves; and (iii) examine their associations with the Forest Flammability Index (FFI) and Management Effectiveness Evaluation (MEE) to provide a more comprehensive framework for comparative forest fire assessment.

## **2. Data and Methods**

### **2.1. Study Area**

We focus on the TRs in the central India (spanning 19° - 25° N latitude and 77° - 82° E longitude), which hosts rich biodiversity and important protected area. The climate of the selected region is characterized by a hot summer (March-June), rainy monsoon (July-September) and dry winter (November - February) (IMD, 2020; Attri & Tyagi, 2010). The broader central Indian landscape comprises approximately 19 tiger reserves (NTCA, 2025; Qureshi et al. 2023). Only 14 TRs for which the Management Effectiveness Evaluation (MEE) scores are designated in 2022 are included in this study (Yadav et al. 2023).

**Table 1: Detailed geographical, ecological and administrative information of TRs**

| <b>Tiger Reserve (TR)</b>               | <b>Estimated Area (km<sup>2</sup>)</b> | <b>MEE Score (%) (Yadav et al., 2023)</b> | <b>Ecological Importances (Qureshi et al. 2023)</b> |
|-----------------------------------------|----------------------------------------|-------------------------------------------|-----------------------------------------------------|
| Indravati Tiger Reserve (IDTR)          | 2922.39                                | 53.79                                     | Major tiger habitat; extensive inviolate core       |
| Udanti-Sitanadi Tiger Reserve (USTR)    | 1794.91                                | 56.82                                     | Wildlife corridor; wild buffalo habitat             |
| Achanakmar Tiger Reserve (AKTR)         | 936.33                                 | 69.7                                      | Diverse deciduous forest; rugged terrain            |
| Sanjay-Dubri Tiger Reserve (SDTR)       | 1482.34                                | 71.97                                     | Corridor linking Bandhavgarh–Palamu                 |
| Bor Tiger Reserve (BRTR)                | 131.48                                 | 77.27                                     | Corridor between PMHTR and TATR                     |
| Bandhavgarh Tiger Reserve (BGTR)        | 1608.42                                | 83.33                                     | High tiger density                                  |
| Navegaon - Nagzira Tiger Reserve (NNTR) | 1769.34                                | 83.33                                     | Fragmented landscape; human–wildlife conflict       |
| Panna Tiger Reserve (PNTR)              | 1782.86                                | 83.33                                     | Successful tiger reintroduction site                |
| Melghat Tiger Reserve (MGTR)            | 2037.9                                 | 84.85                                     | Dry deciduous forest; secure core                   |
| Tadoba- Andhari Tiger Reserve (TATR)    | 1639.65                                | 87.88                                     | Major tiger source population                       |
| Pench MP Tiger Reserve (PMPTR)          | 1163.22                                | 89.39                                     | High ecological connectivity                        |
| Pench MH Tiger Reserve (PMHTR)          | 743.92                                 | 90.91                                     | Well-managed Pench–Kanha corridor                   |
| Kanha Tiger Reserve (KNTR)              | 1961.92                                | 91.67                                     | Barasingha conservation landscape                   |
| Satpura Tiger Reserve (SPTR)            | 2033.79                                | 93.18                                     | Intact corridors; benchmark conservation            |

95 Table 1 provides characteristic of TRs such as geographical area, ecological importance, and  
 96 MEE score. These TRs are known for their higher susceptibility to the pre-monsoon forest fire  
 97 activities (Jain et al. 2021). Most of the TRs are primarily surrounded by agricultural, with

nearby rural and tribal settlements (Reddy et al., 2017). Boundaries of TRs (Figure 1) are delineated and presented on the map of India (Survey of India, 2025) sourced by National Tiger Conservation Authority (NTCA), Government of India (NTCA, 2025).

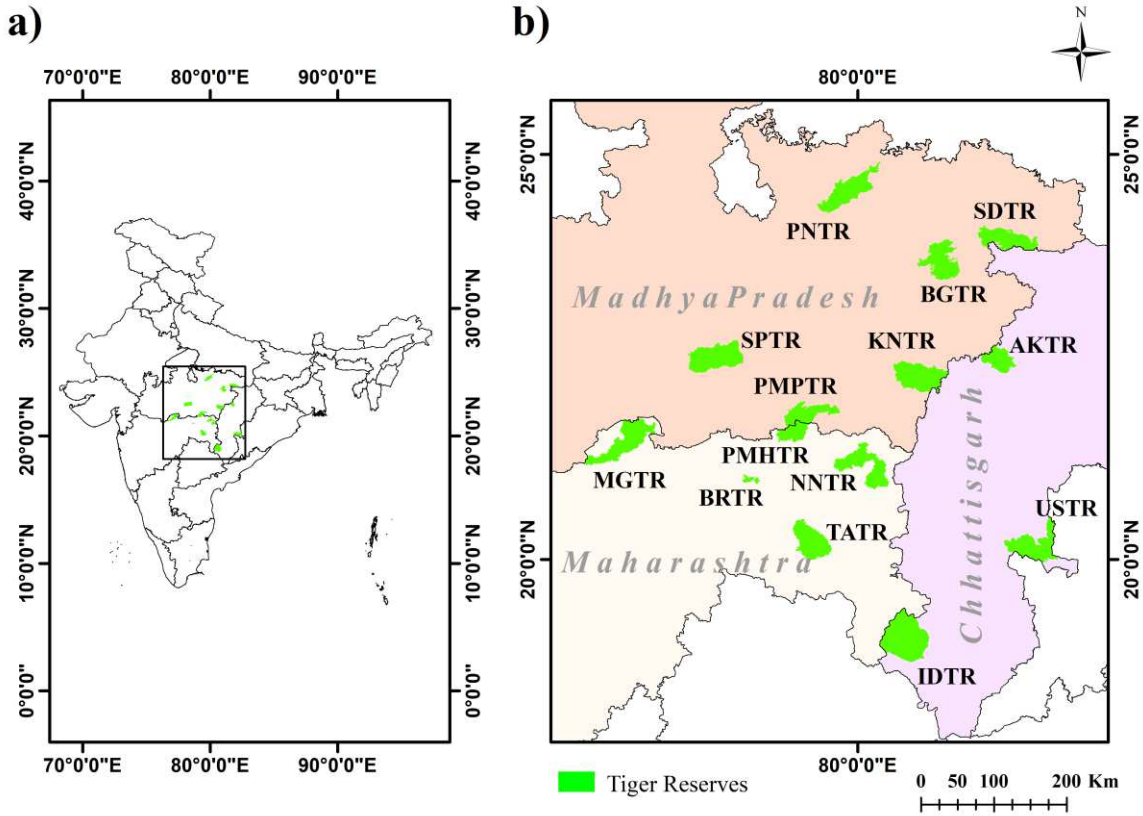


**Fig. 1: Study area map a) map of India with TRs; b) Central India map with 14 TRs.**

## 2.2. Data acquisition

The present study utilizes multiple MODIS-based datasets to analyse forest fire dynamics. These include active fire data, burned area products all with long-term temporal coverage, and land cover information, other administrative data alongside, ensuring reliable multi-decadal fire assessment. The detailed information of the data acquisition is given in Table 2, and the structured framework of the MEE is provided in Table S1 of the Supplementary Information.

110

**Table 2: Details of the dataset used in the study**

| <b>Dataset</b>                         | <b>Period /<br/>Accessed Date</b>      | <b>Source/Product</b>                                           | <b>Key Information</b>                                                         |
|----------------------------------------|----------------------------------------|-----------------------------------------------------------------|--------------------------------------------------------------------------------|
| <b>Satellite Data</b>                  |                                        |                                                                 |                                                                                |
| Active fire<br>(Resolution – 1<br>km)  | 2001 – 2022<br>(Annually<br>Averaging) | MODIS NRT (Terra &<br>Aqua); NASA FIRMS<br>(Giglio et al. 2016) | Annual fire<br>occurrence; near-real-<br>time detection                        |
| Burned area<br>(Resolution – 500<br>m) | 2001 – 2022<br>(Annually<br>Averaging) | MCD64A1 (V6), LP<br>DAAC<br>(Giglio, 2020)                      | Monthly global<br>burned area; based on<br>reflectance and active<br>fire data |
| Land cover<br>(Resolution – 500<br>m)  | 2020                                   | MCD12Q1 (V6.1)<br>(Friedl. et al., 2019)                        | IGBP classification;<br>17 land cover classes                                  |
| <b>Ancillary Data</b>                  |                                        |                                                                 |                                                                                |
| MEE score                              | 2022                                   | NTCA MEE report<br>2022 (Yadav et al.,<br>2023)                 | Forest management<br>and preparedness                                          |
| TR boundary                            | 2022                                   | NTCA and Forest<br>Department<br>(NTCA 2025)                    | TR boundary to use<br>in geospatial analysis                                   |

111

112 Note that both MODIS active fire and burned area products have undergone extensive  
 113 validation using independent high-resolution datasets such as ASTER and Landsat, achieving  
 114 Stage 3 validation (Giglio, 2020; Giglio et al., 2018). Land cover data has achieved Stage 2  
 115 validation based on cross-validation of the training dataset (Sulla-Menashe et al., 2018).

116 Following data collection, the overall workflow used in this study can be illustrated in Figure  
 117 2. The method consists of the following major steps: data processing, derivation of fire metrics,  
 118 and statistical analysis.

### 119 **2.3. Data processing**

120 Spatial datasets are processed using GIS software (QGIS 3.40.6 and ArcGIS Version 10.7.1).  
 121 Initially, TR boundaries are reprojected to the Universal Transverse Mercator (UTM)

coordinate system (WGS 84, Zone 44N) for accurate area estimation. For consistency, the total area of each TR is computed using GIS-based area calculation methods. Burned area and fire occurrence datasets are then clipped to the boundaries of the respective TRs. All the MODIS-detected fire events are considered, and no filtering is applied. Similarly, burned area data derived from the MCD64A1 product are extracted for each TR for each month which is then aggregated annually. Fire occurrence and burned area are used to derive the proposed metrics. Further, forest type distribution within each TR is determine using the MODIS Land Cover Type 1 dataset (pre-classified categories). TRs are already a conserved and reserved area since decade with the highest protection and management resources (Koulgi et al., 2019). Although localized vegetation changes may have occurred during the study period, tiger reserves are legally protected landscapes (reference year 2020 used, intended to characterize relative vegetation-associated flammability rather than annual land-cover dynamics). Forest type-wise burned area is estimated by overlaying the annual burned area with the forest type layer.

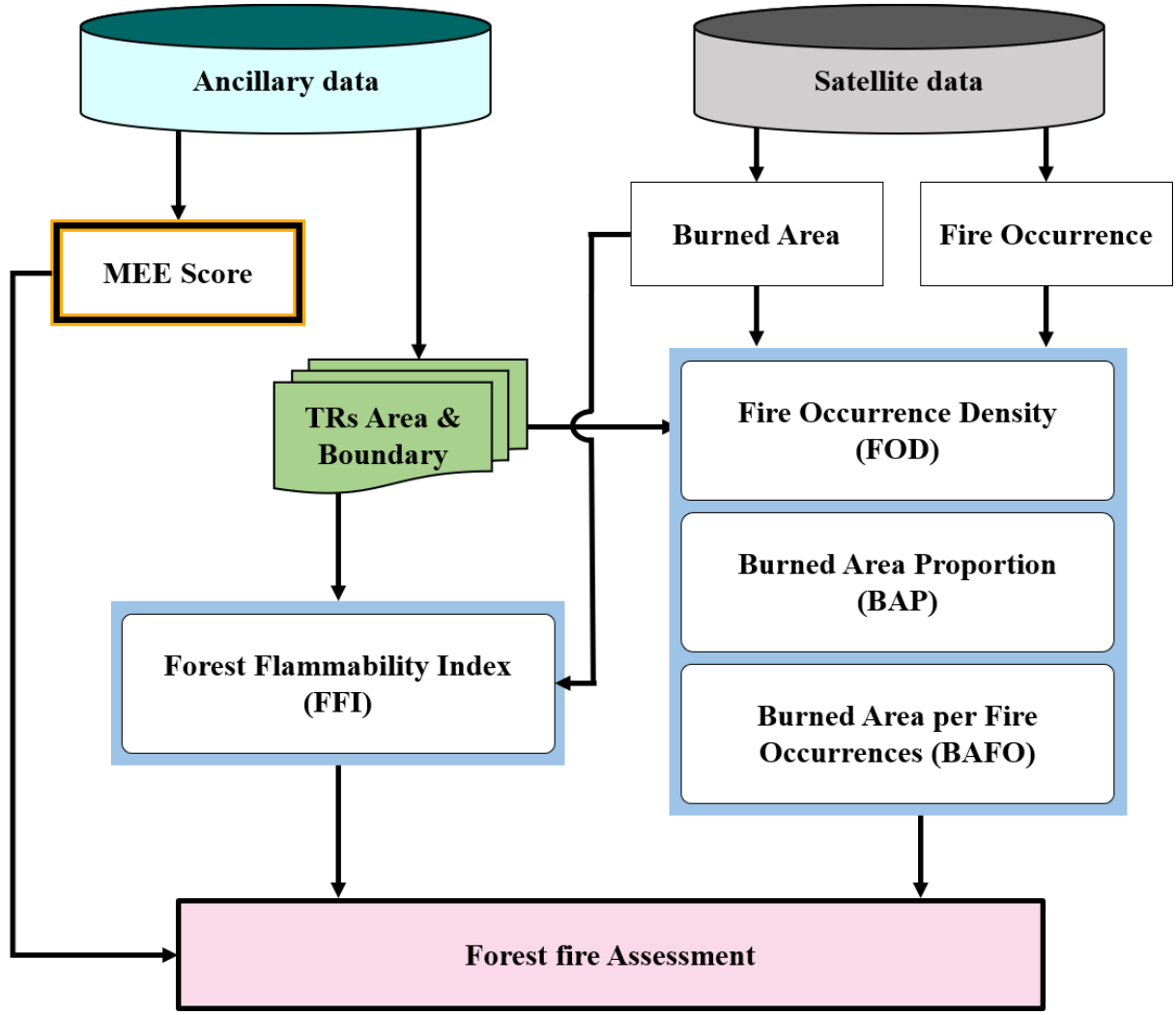


**Fig. 2: Schematic representation of the workflow of the study.**

#### 2.4. Metrics for Forest Fire Assessment

Conventionally, forest fires are assessed using annual fire occurrence (defined as the number of MODIS active fire detections) and annual burned area. In this study, we derive the composite metrics: i) Fire Occurrence Density (FOD), ii) Burned Area Proportion (BAP), and iii) Burned Area per Fire Occurrence (BAFO). The formulation of these metrics is as follows.

For the  $n^{th}$  forest in the  $y^{th}$  year, the average number of fire incidences per year,  $N_{fny}$  and average burned area represents the area of the forest burned,  $A_{bny}$  per year.

FOD is defined as the average number of fire occurrences per unit area for the  $n^{th}$  forest with total area  $A_{Tn}$ , i.e.,

$$FOD_n = \frac{1}{22} \frac{\sum_{y=1}^{22} N_{fny}}{A_{Tn}} \dots\dots\dots (1)$$

BAP is defined as the average burned area proportion for the  $n^{th}$  forest with respect to  $A_{Tn}$  i.e.,

$$BAP_n = \frac{1}{22} \frac{\sum_{y=1}^{22} A_{bny}}{A_{Tn}} \times 100 \dots\dots\dots (2)$$

BAFO is defined as a ratio of average burned area to the average number of fire occurrences for the  $n^{th}$  forest, i.e.,

$$BAFO_n = \frac{\sum_{y=1}^{22} A_{bny}}{\sum_{y=1}^{22} N_{fny}} \dots\dots\dots (3)$$

Conventional metrics may produce misleading comparisons when forests of different sizes show similar fire counts, larger forests naturally tend to have more fires. The same limitation affects burned-area assessments, as size can bias the interpretation. To address this, we use composite metrics, i.e. FOD, BAP and BAFO. Among these, FOD and BAP are normalized with respect to the total area of the respective forest. FOD represents fire frequency per unit area, whereas BAP reflects the extent of damage or impact of fires within a forest, i.e. the percentage of total forest area affected by fires. On the other hand, BAFO represents the average burned area associated with each MODIS active fire detection and provides a complementary descriptor of fire spread characteristics. Among these, BAFO is more likely to reflect forest characteristics such as forest type, local climate, management effectiveness, and topography.

#### **Relative Forests Flammability:**

Apart from the composite metrics, we employ Forest Flammability index (FFI), representing

relative flammability of the forest with respect to the forests under consideration. In general, the central Indian TRs comprise nine major land cover classes (Figure 3). Land cover data with 17 pre-classified categories (Friedl et al., 2019) are used to determine forest types distribution within TRs. Six forest types are selected for analysis based on their susceptibility to fire spread (Table 3). Figure 3 shows the land cover distribution across the 14 TRs. These maps provide the spatial basis for calculating the FFI, which quantifies the relative contribution of different forest types to fire spread. The characteristics and flammability of forest types found in central Indian TRs are listed in (Table 3), and detailed are provide in (Table S2 supplementary information). The major forest types consist deciduous forests, savannas, grasslands, woody savanna, and mixed forest. These forest types exhibit distinct flammability characteristics, which varies with climatic conditions and are difficult to quantify directly (Simpson et al., 2016). Therefore, relative flammability ( $W_m$ ) is estimated statistically using burned area contributions of individual forest types in 14 TRs.

Let here be  $N$  (14) forests with  $M$  (6) flammable forest types in each forest, observed over 22 years. The total flammable area (comprising the  $M$  (6) forest types) of the  $n^{th}$  forest is  $A_n$ , and the area of the  $m^{th}$  forest type in the  $n^{th}$  forest is  $AF_{nm}$  (assumed constant over the duration), and the burned area of the  $m^{th}$  forest type in the  $n^{th}$  forest for the  $y^{th}$  year is denoted as  $BAF_{nmy}$ .

The  $W_m$  indicates the relative flammability of the forest type. i. e. the percentage of burned area for the  $m^{th}$  forest type is given as,

$$W_m = \frac{1}{Y} \frac{\sum_{y=1}^{22} BAF_{nmy}}{AF_{nm}} \times 100 \quad \dots\dots\dots (4)$$

The Forest Flammability Index ( $FFI$ ) for the  $n^{th}$  forest is defined as,

$$FFI_n = \sum_{m=1}^M \frac{AF_{nm}}{A_n} \times W_m \quad \dots\dots\dots (5)$$

*FFI* integrates the spatial extent of fire spread by assigning proportional weight to different forest types, thereby assessing their relative contribution to overall forest flammability. Finally, the *FFI* and the derived fire metrics are subjected to statistical analysis.

**Table 3: Characteristics and Flammability of Forest types details.**

| S.N. | Forest type                | Vegetation Type (Strahler et al. 1999)                                                                                                                            | Fuel Characteristics                                                                                                                                                                                                                                                                                                                                  |
|------|----------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1    | Deciduous Broadleaf Forest | Dominated by woody vegetation (>60%) and height exceeding 2 meters. Broadleaf trees with an annual cycle of leaf-on and leaf-off periods.                         | Dominated species: Sal and Teak<br>Flammable due to abundant dry leaf litter and seasonal dryness (Behera et al., 2024; Rathaudd et al.2025, Ray et al., 2025, Kumar et al., 2022, Pati et al., 2024).                                                                                                                                                |
| 2    | Grasslands                 | Dominated by Herbaceous land cover                                                                                                                                | Fastest-spreading short lived fires, ( Bond & Keeley, 2005; Jain et al. 2021, Niyogi 2025, Ray et al., 2025, Simpson et al. 2015)                                                                                                                                                                                                                     |
| 3    | Savannas                   | Herbaceous with forest canopy cover between 10-30%.                                                                                                               | Flammable due to seasonal leaf litter. Common in reserves like SPTR (Jain et al. 2021, Ray et al., 2025, Simpson et al. 2015).<br>Grass matrix with scattered trees (Acacia catechu, Butea monosperma, Anogeissus species.) (Bond et al., 2005; Archibald et al., 2010) .                                                                             |
| 4    | Woody Savanna              | Herbaceous with forest canopy cover between 30-60%.                                                                                                               | Relatively less flammable, limited spatial extent in to other forests (Jain et al. 2021; Niyogi 2025; Ray et al., 2025)<br>Fire spread decreases with tree cover but increases with shrub invasion and fuel accumulation. Lantana camara significantly enhances fine fuel continuity and fire intensity (Bowman et al., 2009; Archibald et al., 2010) |
| 5    | Mixed forests              | Trees with a percent cover >60% and height exceeding 2 meters. Consists of tree communities with interspersed mixtures or mosaics of the other four forest types. | Mixed and moist deciduous forest types exhibit patchy and irregular fires (Jain et al., 2021, Ray et al., 2025).                                                                                                                                                                                                                                      |
| 6    | Cropland                   | Crops followed by harvest and a bare soil period (e.g., single and multiple cropping systems).                                                                    | Not a natural fire ecosystem but often contributes significantly to seasonal ignitions through stubble burning, intentional clearing, or accidental fires. (Ray et al., 2025).                                                                                                                                                                        |

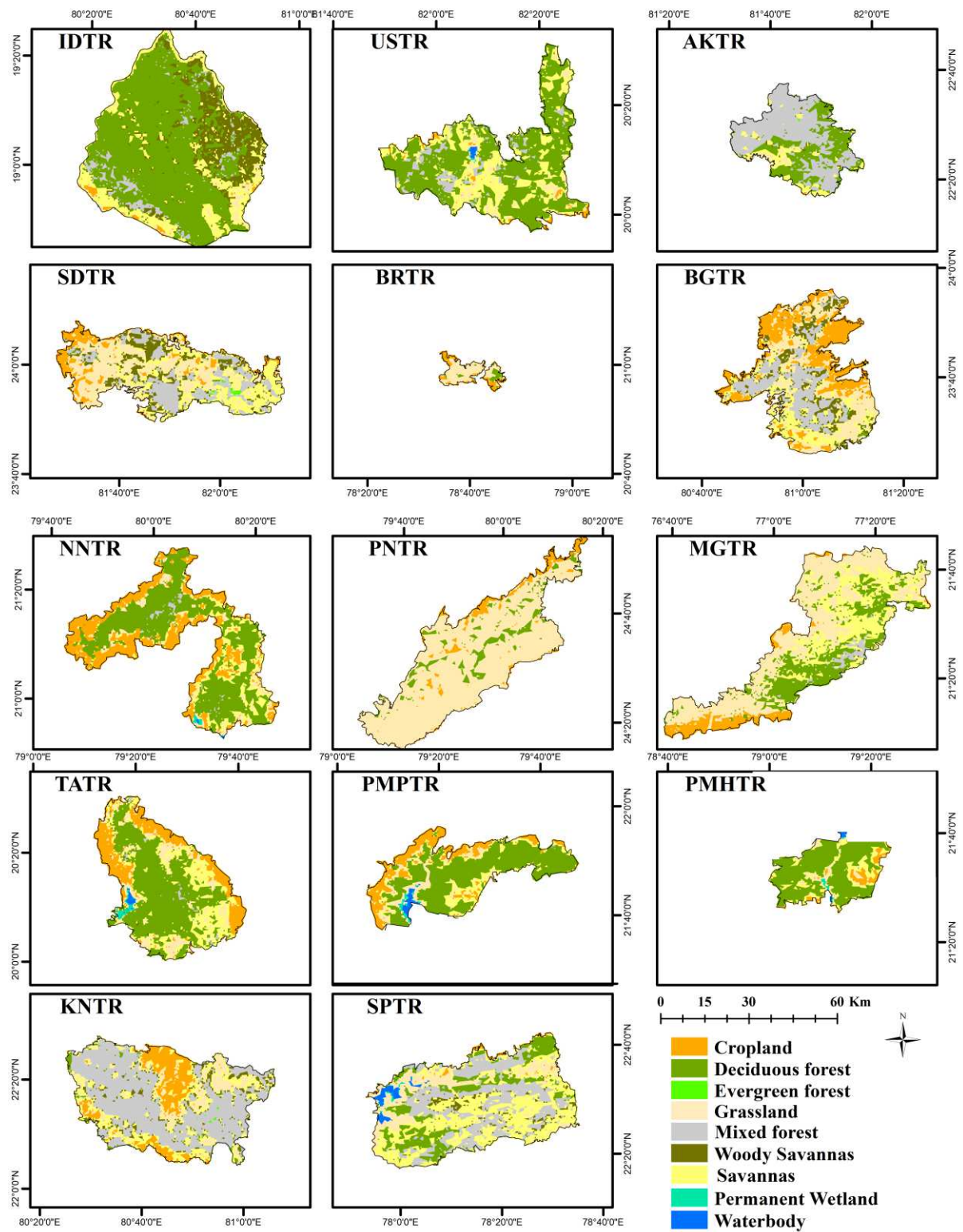


**Fig. 3 : Forest types in the TRs (Source: (Friedl et al., 2019) )**

## 2.5. Statistical analysis

Pearson's correlation (Pearson, K. 1920) is used to assess the strength and direction of the linear relationship between two variables (Fire Occurrence, Burned Area, FOD, BAP, BAFO, MEE and FFI). The analysis is used to examine descriptive associations of the pair of variables. The Pearson correlation coefficient ( $r$ ) between the pair of variables ( $X, Y$ ) is calculated as:

$$r = \frac{\text{Covariance between } X \text{ and } Y}{\text{Standard deviation of } X \times \text{Standard deviation of } Y}$$

## 3. Results

Figure 4 a) presents, annual average of fire occurrence and burned area for 22 years (2001-2022) of 14 TRs (arranged in increasing order of MEE score). We can see that, significant variation in terms of burned area (454.83 - 5.9 km<sup>2</sup> /year) and fire occurrences (204 - 8 /year) in the TRs. IDTR stands out with significantly higher annual average of 204 fires per year and burned area of 454.83 km<sup>2</sup> per year. Lowest of fire occurrences (8/year) and burned area (5.9 km<sup>2</sup>/year) are seen for BRTR and PMHTR, respectively. MGTR, TATR and USTR also showed high fire activity, averaging 135, 90 and 89 fires/year, and corresponding burned area

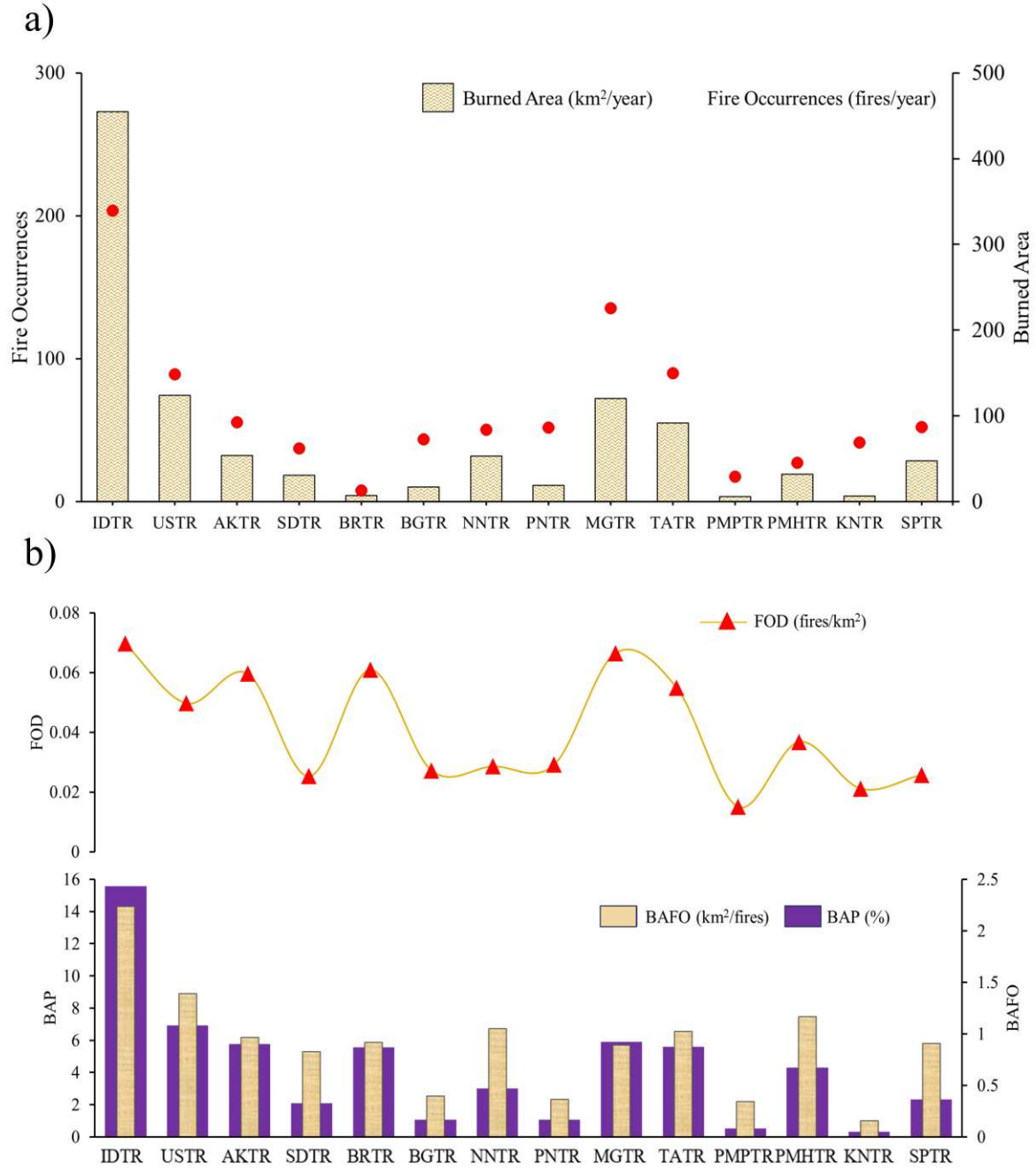


**Fig 4: a) Conventional approach: fire occurrences and burned area; b) Proposed approach: FOD, BAP, and BAFO**

of 120.29, 91.97 and 123.94 km<sup>2</sup>/year, respectively. NNTR exhibits higher burned area per year (53.15 km<sup>2</sup>/year) than KNTR (6.35 km<sup>2</sup>/year), SPTR (47.51 km<sup>2</sup>/year) and PNTR (18.71 km<sup>2</sup>/year), but has lower or similar fire frequency (50.54 /year). A similar pattern was observed for SDTR (fire frequency 37.41 /year and burned area 30.9 km<sup>2</sup>/year) and PMHTR (fire frequency 27.36 /year and burned area 31.93 km<sup>2</sup>/year) as against PNTR (fire frequency 51.9

/year and burned area 18.71 km<sup>2</sup>/year), BGTR (fire frequency 43.68 /year and burned area 17.37 km<sup>2</sup>/year) and KNTR (fire frequency 41.45 /year and burned area 6.35 km<sup>2</sup>/year). On the other hand, the results for the derived forest fire assessment metrics, i.e. FOD, BAP, and BAFO, are presented in Figure 4 b). Highest FOD is observed for IDTR (~ 0.07 fires/ km<sup>2</sup>) and the lowest for PMPTR (~ 0.01 fires/ km<sup>2</sup>). Whereas the maximum BAP (15.5%) and BAFO (~ 2.2 km<sup>2</sup>/fire) is exhibited by IDTR and the lowest by KNTR, (0.2 %) and BAFO (~ 0.2 km<sup>2</sup>/fire).

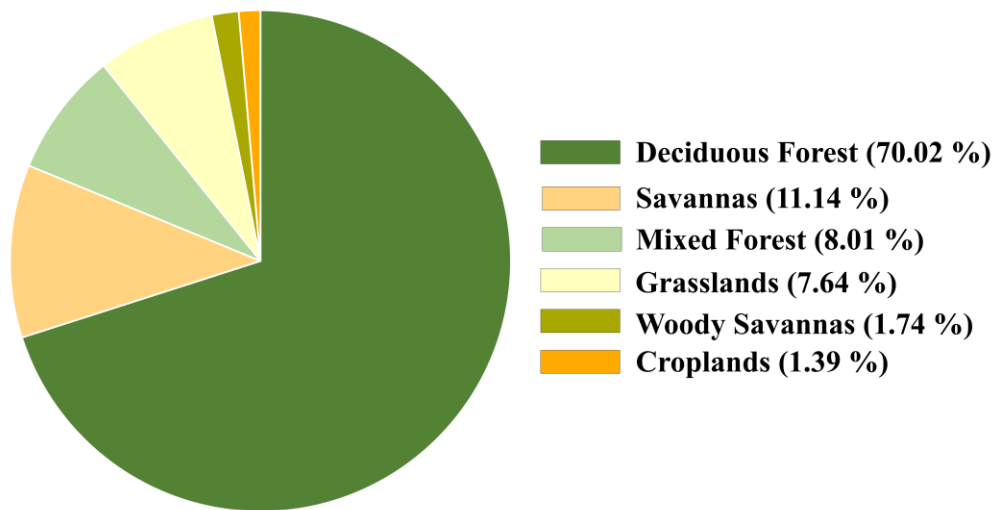


**Fig. 5: Relative flammability of forest types ( $W_m$ ) for central Indian TRs**

Table S7 compares conventional fire metrics (fire occurrence and burned area) with the proposed normalized metrics (FOD, BAP, and BAFO). Several Tiger Reserves (TRs) exhibited contrasting fire characteristics after normalization. Indravati TR recorded the highest burned area (454.83 km<sup>2</sup>) and fire occurrence (203.59 detections), together with the highest BAP (15.56%), FOD (0.070 detections km<sup>-2</sup>), and BAFO (2.23 km<sup>2</sup> per detection), indicating the greatest relative fire impact. In contrast, Pench MP TR (PMPTR) consistently exhibited the lowest values for both conventional and normalized fire metrics.

Although fire occurrence and burned area provide useful measures of fire activity, they do not account for differences in reserve size. Consequently, the normalized metrics provide a complementary framework for standardized comparison among Tiger Reserves. (Figure 4b), i.e. FOD, BAP, and BAFO, as defined in equation (1), (2) and (3), respectively. Here, FOD and BAP provide normalized values of fire occurrences and burned area, respectively, with respect to the area of the TR. Whereas, BAFO represents burned area per occurrence, which depends on the flammability of the forest. All these derived metrics are also controlled by the effective management. This suggests that these metrics provide better understanding of forest characteristics (in terms of flammable forest types) and effectiveness of the forest management (in terms of MEE Score). Accordingly, we analyse the variations of FOD, BAP and BAFO within the 14 TRs.

We statistically determine the relative flammability of forest type  $W_m$  (Figure 5), which indicates deciduous forest type to be the most flammable (70.02%), followed by savannas (11.14%). mixed forest (8.01%) and grasslands (7.64%) have comparatively smaller  $W_m$  values (Table S8). The area of flammable forest types across Central Indian TRs are given in Table S3 (supplementary information), and FFI calculation provide in section S2 of supplementary information. We find that FFI values (calculated using equation 5) for USTR (47.50) and IDTR (47.20) are similar, which are also the highest amongst the 14 TRs. While relatively lower FFI values are observed in SDTR (7.45), BRTR (7.00) and BGTR (6.55). Additionally, NNTR (37.1), AKTR (34.37), and TATR (34.61) also exhibited relatively high FFI values. Moderate FFI are observed in MGTR (19.79) and SPTR (14.54), reflecting intermediate fire spread patterns. In contrast, TRs such as PMPTR (40.03) and PMHTR (44.94) appear as anomalies. FFI was inversely associated with MEE (Figure 6). Tiger Reserves with relatively higher MEE scores generally exhibited lower BAFO and BAP values; however, these relationships represent statistical associations rather than evidence of causal effects. MEE scores ranged

from 53.79 for IDTR to 93.18 for SPTR, whereas TRs such as KNTR and PMHTR have MEE scores of 91.67 and 90.91, respectively.

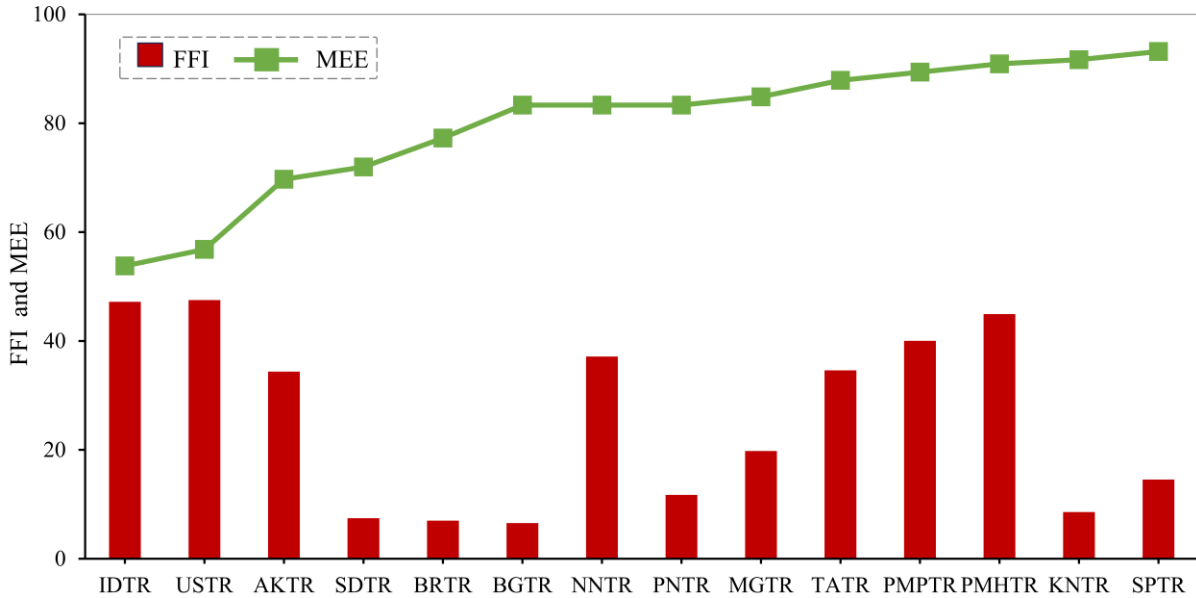


**Fig 6: FFI values and MEE Scores of TRs**

Further, Pearson's correlation analysis is performed (Table 4) amongst the variables including FFI and MEE Score. The t-statistics, and p-values of correlation are presented in the Table S4. The outcomes reveal that FFI has a strong positive correlation with BAFO ( $r = 0.64$ ,  $p\text{-value} = 1.9 \times 10^{-03}$ ), BAP ( $r = 0.54$ ,  $p\text{-value} = 1.1 \times 10^{-02}$ ), and burned area ( $r = 0.50$ ,  $p\text{-value} = 2.2 \times 10^{-02}$ ). Whereas the correlation between FOD and FFI is relatively weak ( $r = 0.30$ ,  $p\text{-value} = 1.8 \times 10^{-01}$ ). MEE score is found to strongly influence on BAP ( $r = -0.73$ ,  $p\text{-value} = 1.5 \times 10^{-04}$ ), BAFO ( $r = -0.70$ ,  $p\text{-value} = 4.2 \times 10^{-04}$ ), and burned area ( $r = -0.67$ ,  $p\text{-value} = 8.3 \times 10^{-04}$ ), while it moderately affects the fire occurrence ( $r = -0.55$ ,  $p\text{-value} = 9.4 \times 10^{-03}$ ) and FOD ( $r = -0.56$ ,  $p\text{-value} = 8.9 \times 10^{-03}$ ). Both MEE and FFI show stronger associations with spread-dependent metrics (BAFO, BAP, and burned area) than with fire occurrences-based metrics (FOD and Fire occurrence).

**Table 4: Pairwise Pearson correlation coefficients (r) and significance among fire-related variables and MEE Score.**

| SN | Variable 1      | Variable 2  | r     | Significance level |
|----|-----------------|-------------|-------|--------------------|
| 1  | Fire Occurrence | Burned Area | 0.92  | ****               |
| 2  | Fire Occurrence | BAFO        | 0.71  | ****               |
| 3  | Fire Occurrence | FOD         | 0.65  | ****               |
| 4  | Fire Occurrence | BAP         | 0.82  | ****               |
| 5  | Fire Occurrence | FFI         | 0.40  | *                  |
| 6  | Fire Occurrence | MEE Score   | -0.55 | ****               |
| 7  | Burned Area     | BAFO        | 0.85  | ****               |
| 8  | Burned Area     | FOD         | 0.61  | ****               |
| 9  | Burned Area     | BAP         | 0.92  | ****               |
| 10 | Burned Area     | FFI         | 0.50  | **                 |
| 11 | Burned Area     | MEE Score   | -0.67 | ****               |
| 12 | BAFO            | FOD         | 0.68  | ****               |
| 13 | BAFO            | BAP         | 0.93  | ****               |
| 14 | BAFO            | FFI         | 0.64  | ****               |
| 15 | BAFO            | MEE Score   | -0.70 | ****               |
| 16 | FOD             | BAP         | 0.83  | ****               |
| 17 | FOD             | FFI         | 0.30  | NS                 |
| 18 | FOD             | MEE Score   | -0.56 | ****               |
| 19 | BAP             | FFI         | 0.54  | ***                |
| 20 | BAP             | MEE Score   | -0.73 | ****               |
| 21 | FFI             | MEE Score   | -0.37 | *                  |

Significance levels: \*\*\*\*  $p \leq 0.01$ ; \*\*\*  $p \leq 0.02$ ; \*\*  $p \leq 0.05$ ; \*  $p \leq 0.10$ ; NS = not significant.

#### 4. Discussion

This study complements conventional fire metrics with normalized descriptors that enable standardized comparison among Tiger Reserves of different geographical extents. FOD, BAP, and BAFO capture complementary dimensions of fire activity by representing fire concentration, proportional burned area, and the average burned area associated with each active fire detection, respectively. The variability observed across the 14 Tiger Reserves highlights the limitations of conventional metrics for inter-reserve comparison and

demonstrates the value of normalized indicators for heterogeneous landscapes (Andela et al., 2019).

The results indicate that fire spread, rather than fire frequency alone, is an important dimension of fire regimes in central Indian forests. For example, KNTR recorded 41.45 fires year<sup>-1</sup> but had a BAFO of only 0.15 km<sup>2</sup> fire<sup>-1</sup>, whereas PMHTR experienced fewer fire occurrences (27.36 year<sup>-1</sup>) but a much higher BAFO (1.17 km<sup>2</sup> fire<sup>-1</sup>), indicating larger average burned areas per active fire detection. Similarly, NNTR and AKTR exhibited comparable burned areas but substantially different BAP values, reflecting contrasting proportional fire impacts after accounting for reserve size. These observations are consistent with global evidence that a relatively small proportion of fires contributes disproportionately to total burned area (Andela et al., 2019; Giglio et al., 2018), suggesting that frequency-based metrics alone may not adequately characterize landscape-scale fire impacts (Archibald et al., 2013).

Vegetation characteristics also influence fire dynamics. Deciduous-dominated forests, which accumulate substantial dry litter during the pre-monsoon season, exhibit higher flammability and enhanced fire spread potential (Bowman et al., 2009; Kumar et al., 2022). The FFI provides a relative measure of vegetation-driven fire susceptibility; however, the observed variability among reserves indicates that flammability alone does not explain fire activity and should be interpreted alongside management and environmental factors (Pausas & Keeley, 2009; Archibald et al., 2013). The strong negative associations between MEE scores and spread-dependent metrics (BAP, BAFO, and burned area) further suggest that effective management primarily limits fire extent rather than ignition frequency. Reserves with high flammability and lower MEE scores, such as Indravati and Udanti-Sitanadi, generally exhibited greater fire activity than better-managed reserves (Table S6) (Yadav et al., 2023).

The significant correlations among burned area, BAP, and BAFO emphasize the importance of fire spread in determining overall fire impact, whereas the weaker association between FOD and FFI indicates the comparatively limited explanatory value of frequency-based metrics. Since FOD, BAP, and BAFO are derived from fire occurrence and burned area, these correlations are expected and should not be interpreted as evidence of independent predictive relationships. Instead, they support the consistency of the proposed descriptors for comparative fire assessment.

Ecologically, higher BAP and BAFO values indicate more extensive fire spread and greater average burned area per active fire detection, which may contribute to habitat degradation, biomass loss, and adverse effects on wildlife populations, including tigers (Qureshi et al., 2023) (Table S5). Conversely, lower spread metrics are associated with more controlled fire regimes that may enhance ecosystem resilience (Bond & Keeley, 2005). Overall, the findings suggest that fire regimes in central Indian forests are associated with the interaction of fire spread, vegetation characteristics, and management effectiveness.

### ***Limitations of the study***

Despite its merits, the proposed approach has several limitations. First, the reliance on MODIS-derived datasets introduces uncertainty due to their moderate spatial resolution, which may omit small or low-intensity fires. Accordingly, the proposed metrics should be interpreted as regional-scale comparative indicators derived from a consistent long-term satellite record rather than absolute estimates of burned area. Although MODIS fire products have undergone Stage-3 validation (Giglio et al., 2018), omission errors remain, particularly at finer spatial scales (Boschetti et al., 2019). Second, BAP and BAFO characterize fire spread and spatial extent but do not explicitly account for fire intensity or severity, which are important for assessing ecological damage and post-fire recovery (Keeley, 2009). Third, the MODIS Active

Fire product records thermal anomaly detections rather than individual fire events; consequently, repeated detections of the same fire may contribute to reported fire occurrence. Therefore, the proposed metrics represent long-term satellite-observed fire activity rather than reconstructed fire-event statistics.

A single reference-year (2020) land-cover dataset was used to characterize vegetation throughout the study period, and temporal changes in vegetation composition were not incorporated. Consequently, the FFI should be interpreted as a relative indicator of vegetation-driven fire susceptibility and does not explicitly account for climatic variability, fuel moisture, or topographic influences, all of which affect fire dynamics (Kelley et al., 2019). Similarly, MEE scores provide a broad measure of management effectiveness but may not fully capture real-time operational efficiency or localized fire response.

## **5. Conclusions**

This study develops and evaluates composite forest fire assessment metrics (FOD, BAP, and BAFO) across 14 central Indian tiger reserves using MODIS-derived datasets (2001–2022). The results demonstrate that conventional metrics alone are insufficient to capture the complexity of fire regimes, whereas BAP and BAFO provide improved characterization of fire spread and landscape-level impact. BAP captures the proportional extent of burned area, while BAFO reflects the average size of individual fire events across the forests. Fire regimes in central India are primarily associated with fire spread dynamics rather than fire frequency alone. Pearson's correlation analysis showed stronger associations of BAP and BAFO with burned area than FOD. Further, fire spread is found to be strongly influenced by the vegetation characteristics and management effectiveness. Highly flammable deciduous-dominated reserves, such as IDTR and USTR, exhibit elevated fire activity, particularly under lower MEE scores. The FFI provides a useful relative measure of vegetation-driven fire susceptibility,

while MEE highlights the critical role of governance in constraining fire extent. Ecologically, the results emphasize that region prone to extensive fires can cause habitat degradation and negatively affect wildlife, whereas controlled fire regimes may support ecosystem resilience. Overall, we provide a unified context linking fire extent, flammability, and management effectiveness for improved fire monitoring, policy, and conservation planning.

## References:

1. Ahmad, F., & Goparaju, L. (2019). Forest fire trend and influence of climate variability in India: a geospatial analysis at national and local scale. *Ekológia*, 38(1), 49-68. <https://doi.org/10.2478/eko-2019-0005>
2. Andela, N., Morton, D. C., Giglio, L., Chen, Y., van der Werf, G. R., Kasibhatla, P. S., DeFries, R. S., Collatz, G. J., Hantson, S., Kloster, S., Bachelet, D., Forrest, M., Lasslop, G., Li, F., Mangeon, S., Melton, J. R., Yue, C., & Randerson, J. T. (2017). A human-driven decline in global burned area. *Science*, 356(6345), 1356–1362. <https://doi.org/10.1126/science.aal4108>
3. Andela, N., Morton, D. C., Giglio, L., Paugam, R., Chen, Y., Hantson, S., van der Werf, G. R., & Randerson, J. T. (2019). The Global Fire Atlas of individual fire size, duration, speed and direction. *Earth System Science Data*, 11(2), 529–552. <https://doi.org/10.5194/essd-11-529-2019>
4. Arif, M., Alghamdi, K., Sahel, S., Alosaimi, S., Alsahaft, M., Alharthi, M., & Arif, M. (2021). Role of machine learning algorithms in forest fire management: A literature review. *Journal of Robotics and Automation*, 5, 212-226. <https://doi.org/10.36959/673/372>
5. Attri, S., & Tyagi, A. (2010). *Climate profile of India*. Environment Monitoring and Research Center, India Meteorological Department
6. Archibald, S., Lehmann, C. E. R., Gómez-Dans, J. L., & Bradstock, R. A. (2013). Defining pyromes and global syndromes of fire regimes. *Proceedings of the National Academy*

381 of Sciences of the United States of America, 110(16), 6442–6447.  
 382 <https://doi.org/10.1073/pnas.1211466110>

383 7. Archibald, S., Nickless, A., Govender, N., Scholes, R. J., & Lehsten, V. (2010). Climate  
 384 and the inter-annual variability of fire in southern Africa: A meta-analysis using long-term field  
 385 data and satellite-derived burnt area data. *Global Ecology and Biogeography*, 19(6), 794–809.  
 386 <https://doi.org/10.1111/j.1466-8238.2010.00568.x>

387 8. Bar, S., Acharya, P., Parida, B. R., Sannigrahi, S., Maiti, A., Barik, G., & Kumar, N.  
 388 (2024). Investigation of fire regime dynamics and modeling of burn area over India for the  
 389 twenty-first century. *Environmental Science and Pollution Research*, 31, 53839–53855.  
 390 <https://doi.org/10.1007/s11356-024-32922-w>

391 9. Behera, S., Prusty, B. K., Behera, M. D., & Kale, M. P. (2024). Characterizing fuel  
 392 flammability in a tropical dry community forest in Eastern India using laboratory and remote  
 393 sensing-based approaches. *Tropical Ecology*, 65(3), 399–411. [https://doi.org/10.1007/s42965-](https://doi.org/10.1007/s42965-023-00309-6)  
 394 [023-00309-6](https://doi.org/10.1007/s42965-023-00309-6)

395 10. Bowman, D. M. J. S., Balch, J. K., Artaxo, P., Bond, W. J., Carlson, J. M., Cochrane,  
 396 M. A., D’Antonio, C. M., DeFries, R. S., Doyle, J. C., Harrison, S. P., Johnston, F. H., Keeley,  
 397 J. E., Krawchuk, M. A., Kull, C. A., Marston, J. B., Moritz, M. A., Prentice, I. C., Roos, C. I.,  
 398 Scott, A. C., Swetnam, T. W., van der Werf, G. R., & Pyne, S. J. (2009). Fire in the Earth  
 399 system. *Science*, 324(5926), 481–484. <https://doi.org/10.1126/science.1163886>

400 11. Bond, W. J., & Keeley, J. E. (2005). Fire as a global “herbivore”: The ecology and  
 401 evolution of flammable ecosystems. *Trends in Ecology & Evolution*, 20(7), 387–394.  
 402 <https://doi.org/10.1016/j.tree.2005.04.025>

- 403 12. Boschetti, L., Roy, D. P., Giglio, L., Huang, H., Zubkova, M., & Humber, M. L. (2019).  
404 Global validation of the collection 6 MODIS burned area product. *Remote Sensing of*  
405 *Environment*, 235, 111490. <https://doi.org/10.1016/j.rse.2019.111490>
- 406 13. Davies, D. K., Ilavajhala, S., Wong, M. M., & Justice, C. O. (2008). Fire information  
407 for resource management system: archiving and distributing MODIS active fire data. *IEEE*  
408 *Transactions on Geoscience and Remote Sensing*, 47(1), 72-79.
- 409 14. Dimitrakopoulos, A.P. (2001). A statistical classification of Mediterranean species  
410 based on their flammability components. *International Journal of Wildland Fire*, 10, 113–118.  
411 <https://doi.org/10.1071/WF01004>
- 412 15. Dutta, T., Sharma, S., McRae, B. H., Roy, P. S., & DeFries, R. (2016). Connecting the  
413 dots: mapping habitat connectivity for tigers in central India. *Regional Environmental Change*,  
414 16, 53-67
- 415 16. Friedl, M., & Sulla-Menashe, D. (2019). *MCD12Q1 MODIS/Terra+Aqua Land Cover*  
416 *Type Yearly L3 Global 500 m SIN Grid V006*, NASA Land Processes Distributed Active  
417 Archive Center. <https://doi.org/10.5067/MODIS/MCD12Q1.006>
- 418 17. Forest Survey of India. (2021). *India State of Forest Report 2021*.  
419 <https://fsi.nic.in/forest-report-2021-details>.
- 420 18. Giglio, L., Randerson, J. T., & Van der Werf, G. R. (2013). Analysis of daily, monthly,  
421 and annual burned area using the fourth-generation global fire emissions database (GFED4).  
422 *Journal of Geophysical Research: Biogeosciences*, 118, 317-328.  
423 <https://doi.org/10.1002/jgrg.20042>
- 424 19. Giglio, L., Schroeder, W., & Justice, C. O. (2016). The collection 6 MODIS active fire  
425 detection algorithm and fire products. *Remote Sensing of Environment*, 178, 31-41.  
426 <https://doi.org/10.1016/j.rse.2016.02.054>

20. Giglio, L., Boschetti, L., Roy, D. P., Humber, M. L., & Justice, C. O. (2018). The Collection 6 MODIS burned area mapping algorithm and product. *Remote Sensing of Environment*, 217, 72–85. <https://doi.org/10.1016/j.rse.2018.08.005>
21. Giglio, L., Boschetti, L., & Roy, D. P. (2020). MCD64A1.006 MODIS burned area monthly global 500 m. Earth Engine Data Catalog. <https://doi.org/10.5067/MODIS/MCD64A1.006>
22. Gorain, S., Malakar, A., Dutta, S., & Das, S. (2025). Assessing forest cover, carbon stocks and fire dynamics in India and economic valuation of forest carbon in Asia: a meta-analysis. *Discover Forests*, 1, 16. <https://doi.org/10.1007/s44415-025-00014-3>
23. Hogenbirk, J. C., & Sarrazin-Delay, C. I. (1995). Using fuel characteristics to estimate plant ignitability or fire hazard reduction. *Water, Air, & Soil Pollution*, 82, 161–170. <https://doi.org/10.1007/BF01182830>
24. India Meteorological Department. (2020). *Climatological normals (1981–2010)*. Ministry of Earth Sciences, Government of India.
25. Jobson, J. D. (1991). Multiple linear regression. In *Applied multivariate data analysis: Regression and experimental design* (pp. 219-398). New York, NY: Springer New York. <https://doi.org/10.1007/978-1-4612-0955-3>
26. Jain, M., Saxena, P., Sharma, S., & Sonwani, S. (2021). Investigation of forest fire activity changes over the central India domain using satellite observations during 2001–2020. *GeoHealth*, 5(12), <https://doi.org/10.1029/2021GH000528>
27. Jones, B. A., McDermott, S., Champ, P. A., & Berrens, R. P. (2022). More smoke today for less smoke tomorrow? We need to better understand the public health benefits and costs of prescribed fire. *International Journal of Wildland Fire*, 31(10), 918–926. <https://doi.org/10.1071/WF22025>

- 451 28. Keeley, J. E. (2009). Fire intensity, fire severity and burn severity: A brief review and  
452 suggested usage. *International Journal of Wildland Fire*, 18(1), 116–126.  
453 <https://doi.org/10.1071/WF07049>
- 454 29. Kelley, D. I., Bistinas, I., Whitley, R., Burton, C., Marthews, T. R., & Dong, N. (2019).  
455 *How contemporary bioclimatic and human controls change global fire regimes*. *Nature*  
456 *Climate Change*, 9(9), 690–696. <https://doi.org/10.1038/s41558-019-0540-7>
- 457 30. Kale, M. P., Ramachandran, R. M., Pardeshi, S. N., Chavan, M., Joshi, P., Pai, D.,  
458 Bhavani, P., Ashok, K., & Roy, P. (2017). Are climate extremities changing forest fire regimes  
459 in India? An analysis using MODIS fire locations during 2003–2013 and gridded climate data  
460 of India meteorological department. *Proceedings of the National Academy of Sciences, India*  
461 *Section A: Physical Sciences*, 87, 827–843. <https://doi.org/10.1007/s40010-017-0452-8>
- 462 31. Kale, M. P., Meher, S. S., Chavan, M., Kumar, V., Sultan, M. A., Dongre, P., Narkhede,  
463 K., Mhatre, J., Sharma, N., Luitel, B., Limboo, N., Baingne, M., Pardeshi, S., Labade, M.,  
464 Mukherjee, A., Joshi, U., Kharkar, N., Islam, S., Pokale, S., ... Roy, P. S. (2024). Operational  
465 forest-fire spread forecasting using the WRF-SFIRE model. *Remote Sensing*, 16(13),  
466 2480. <https://doi.org/10.3390/rs16132480>
- 467 32. Kumar, G., Kumar, A., Saikia, P., Roy, P., & Khan, M. (2022). Ecological impacts of  
468 forest fire on composition and structure of tropical deciduous forests of central India. *Physics*  
469 *and Chemistry of the Earth, Parts A/B/C*, 128, 103240.  
470 <https://doi.org/10.1016/j.pce.2022.103240>
- 471 33. Kumar, A., Ray, T., Mohanasundari, T., Jatav, S. S., Chatterjee, U., Shekhar, S., Alam,  
472 E., & Islam, M. K. (2025). Forest fires and climate change in India: impacts, adaptive strategies,  
473 and pathways for climate action (Sustainable Development Goal-13). *Environmental Sciences*  
474 *Europe*, 37, 147. <https://doi.org/10.1186/s12302-025-01195-6>

- 475 34. Koulgi, P. S., Clinton, N., & Karanth, K. K. (2019). Extensive vegetation browning and  
 476 drying in forests of India's Tiger Reserves. *Scientific Reports*, 9, Article 14976.  
 477 <https://doi.org/10.1038/s41598-019-51118-8>
- 478 35. Mani, J.K., & Varghese, A. (2021). Characterization of forest fire frequency using fire  
 479 scar mapping of temporal satellite data for forest fire management. *Journal of Tropical*  
 480 *Forestry and Environment*, 11(2), <https://doi.org/10.31357/jtfe.v11i02.5597>
- 481 36. Mathur, V., Swain, D., Mathur, V., & Negi, H. (2017). Management effectiveness  
 482 evaluation (MEE) of tiger reserves in India: Technical manual (2017–18). National Tiger  
 483 Conservation Authority (NTCA), Government of India.  
 484 [https://ntca.gov.in/assets/uploads/Reports/MEE/Technical\\_Manual\\_MEE%20TR\\_2018.pdf](https://ntca.gov.in/assets/uploads/Reports/MEE/Technical_Manual_MEE%20TR_2018.pdf)
- 485 37. Mak, E.H. (1988). Measuring foliar flammability with the limiting oxygen method.  
 486 *Forest Science*, 34(2), 523-529. <https://doi.org/10.1093/forestscience/34.2.523>
- 487 38. Meng, Q., Huai, Y., You, J., & Nie, X. (2023). Visualization of 3D forest fire spread  
 488 based on the coupling of multiple weather factors. *Computers & Graphics*, 110, 58-68.  
 489 <https://doi.org/10.1007/s00371-024-03408-0>
- 490 39. Nesha, M. K., Herold, M., De Sy, V., Duchelle, A. E., Martius, C., Branthomme, A.,  
 491 Garzuglia, M., Jonsson, O., & Pekkarinen, A. (2021). An assessment of data sources, data  
 492 quality and changes in national forest monitoring capacities in the Global Forest Resources  
 493 Assessment 2005–2020. *Environmental Research Letters*, 16(5), 054029.  
 494 <https://doi.org/10.1088/1748-9326/abd81b>
- 495 40. Niyogi, V. S., Niyogi, R., Banerjee, S., Verma, N., & Choure, K. (2025).  
 496 Environmental and anthropogenic influences on fire patterns in tropical dry deciduous  
 497 forests. *Scientific Reports*, 15, 13272. <https://doi.org/10.1038/s41598-025-98051-7>

- 498 41. National Tiger Conservation Authority (NTCA). (2025). *Decision support system*.  
 499 Ministry of Environment, Forest and Climate Change, Government of India.  
 500 <https://ntca.gov.in/dss/#decision-support-system>
- 501 42. Pati, P. K., Kaushik, P., Malasiya, D., Ray, T., Khan, M., & Khare, P. (2024). Impacts  
 502 of forest fire frequency on structure and composition of tropical moist deciduous forest  
 503 communities of Bandhavgarh Tiger Reserve, Central India. *Trees, Forests and People*, 15,  
 504 100489. <https://doi.org/10.1016/j.tfp.2023.100489>
- 505 43. Pausas, J. G., & Keeley, J. E. (2009). A burning story: The role of fire in the history of  
 506 life. *BioScience*, 59(7), 593–601. <https://doi.org/10.1525/bio.2009.59.7.10>
- 507 44. Pearson, K. (1920). Notes on the history of correlation. *Biometrika*, 13(1), 25-45.
- 508 45. Pellizzaro, G., Cesaraccio, C., Duce, P., Ventura, A., & Zara, P. (2007). Relationships  
 509 between seasonal patterns of live fuel moisture and meteorological drought indices for  
 510 Mediterranean shrubland species. *International Journal of Wildland Fire*, 16, 232–241.  
 511 <https://doi.org/10.1071/WF06081>
- 512 46. Qureshi, Q., Jhala, Y., Yadav, S., & Mallick, A. (2023). Status of Tigers in India-  
 513 2022: Photo-captured Tigers, Summary Report. National Tiger Conservation Authority and  
 514 Wildlife Institute of India. [https://ntca.gov.in/assets/uploads/Reports/AITM/status\\_of\\_tiger-](https://ntca.gov.in/assets/uploads/Reports/AITM/status_of_tiger-copredators-2022.pdf)  
 515 [copredators-2022.pdf](https://ntca.gov.in/assets/uploads/Reports/AITM/status_of_tiger-copredators-2022.pdf)
- 516 47. Rathau, S. K., Irtiga, S., Rahim, P. A., Wani, Z. A., Kothandaraman, S., & Dar, J.  
 517 A. (2025). Disturbance intensity drives structural, compositional and diversity attributes in  
 518 tropical dry forests of Central India. *Trees, Forests and People*, 20, 100864.  
 519 <https://doi.org/10.1016/j.tfp.2025.100864>
- 520 48. Ray, T., Malasiya, D., Verma, A., Purswani, E., Qureshi, A., Khan, M. L., & Verma,  
 521 S. (2023). Characterization of spatial–temporal distribution of forest fire in Chhattisgarh,

522 India, using MODIS-based active fire data. *Sustainability*, 15(9), 7046.  
523 <https://doi.org/10.3390/su15097046>

524 49. Ray, T., Mohanasundari, T., Madguni, O.D., & Rajkumar, M. (2025). Forest Fire  
525 Regimes and Plant Diversity in Tropical Dry Deciduous Forests of Central India. *Journal of*  
526 *Sustainable Forestry*, 1-15. <https://doi.org/10.1080/10549811.2024.2445298>

527 50. Reddy, C. S., Jha, C. S., Manaswini, G., Alekhya, V. P., Pasha, S. V., Satish, K. V.,  
528 Diwakar, P. G., & Dadhwal, V. K. (2017). Nationwide assessment of forest burnt area in India  
529 using Resourcesat-2 AWiFS data. *Current Science*, 112(7), 1521–1532.  
530 <https://doi.org/10.18520/cs/v112/i07/1521-1532>

531 51. Smith, A. C., Wooster, M. J., Powell, S. L., & Usher, D. (2020). Global patterns in fire  
532 size distribution determined from satellite observations. *Nature Communications*, 11, 5649.  
533 <https://doi.org/10.1038/s41467-020-19378-2>

534 52. Strauss, D., Bednar, L., & Mees, R. (1989). Do one percent of the forest fires cause  
535 ninety-nine percent of the damage?. *Forest science*, 35(2), 319-328.  
536 <https://doi.org/10.1093/forestscience/35.2.319>

537 53. Slocum M., Beckage B., Platt W., Orzell S., Taylor W. (2010). Effect of climate on  
538 wildfire size: A cross-scale analysis. *Ecosystems* 13: 828–840. [https://doi.org/10.1007/s10021-](https://doi.org/10.1007/s10021-010-9357-y)  
539 [010-9357-y](https://doi.org/10.1007/s10021-010-9357-y)

540 54. Sulla-Menashe, D., & Friedl, M. A. (2018). *User guide to collection 6 MODIS land*  
541 *cover (MCD12Q1 and MCD12C1) product*. U.S. Geological Survey.

542 55. Sahu, V., Khan, M.A., & Madguni, O.D. (2024). Assessing forest fire dynamics and  
543 risk zones in Central Indian forests: a comparative study of the Khandwa and North Betul forest  
544 divisions of Madhya Pradesh. *Environmental Monitoring and Assessment*, 196, 810.  
545 <https://doi.org/10.1007/s10661-024-12960-0>

56. Sen, M., & Mohan, D. (2024). Can Change in Forest Cover Be Linked to the Management Effectiveness of Protected Areas? The Indian Scenario. *Sustainability*, 16(17), 7431. <https://doi.org/10.3390/su16177431>
57. Survey of India. (2025). *India maps*. Government of India. <https://indiamaps.gov.in/catalog>
58. Sewak, R., Vashisth, M., & Gupta, L. (2021). Forest fires in India: a review. *Journal of University of Shanghai for Science and Technology*, 23, 247-259. <https://doi.org/10.51201/JUSST/21/07129>
59. Simpson, K. J., Ripley, B. S., Christin, P. A., Belcher, C. M., Lehmann, C. E., Thomas, G. H., & Osborne, C. P. (2016). Determinants of flammability in savanna grass species. *Journal of Ecology*, 104(1), 138-148. <https://doi.org/10.1111/1365-2745.12503>
60. Strahler, A., Muchoney, D., Borak, J., Friedl, F., Gopal, S., Lambin, L., & Moody, A. (1999). MODIS land cover product algorithm theoretical basis document (ATBD) (Version 4.0). *NASA Goddard Space Flight Center*.
61. Tamrakar, A., Dixit, B., Singh, S., Prajapati, L., & Chandrakar, S. (2024). Forest fires and non-timber forest products: Assessing impacts and management strategies. *Tuijin Jishu/Journal of Propulsion Technology*, 45, 2024
62. Tyukavina, A., Potapov, P., Hansen, M. C., Pickens, A.H., Stehman, S. V., Turubanova, S., Parker, D., Zalles, V., Lima, A., & Kommareddy, I. (2022). Global trends of forest loss due to fire from 2001 to 2019. *Frontiers in Remote Sensing*, 3, 825190. <https://doi.org/10.3389/frsen.2022.825190>
63. Vadrevu, K. P., Csiszar, I., Ellicott, E., Giglio, L., Badarinath, K., Vermote, E., & Justice, C. (2012). Hotspot analysis of vegetation fires and intensity in the Indian region. *IEEE*

569 *Journal of selected topics in applied Earth Observations and Remote Sensing*, 6, 224-238.

570 <https://doi.org/10.1109/JSTARS.2012.2210699>

571 64. Vadrevu, K. P., Lasko, K., Giglio, L., Schroeder, W., Biswas, S., & Justice, C. (2019).

572 Trends in vegetation fires in South and Southeast Asian countries. *Scientific Reports*, 9, 7422.

573 <https://doi.org/10.1038/s41598-019-43940-x>

574 65. Van Wees, D., van Der Werf, G. R., Randerson, J. T., Andela, N., Chen, Y., &

575 Morton, D.C. (2021). The role of fire in global forest loss dynamics. *Global Change Biology*,

576 27, 2377-2391. <https://doi.org/10.1111/gcb.15591>

577 66. Xiang, M., Xiao, C., Feng, Z., & Ma, Q. (2023). Global distribution, trends and types

578 of active fire occurrences. *Science of the Total Environment*, 902, 166456,

579 <https://doi.org/10.1016/j.scitotenv.2023.166456>

580 67. Yadav, S., Mallick, A., Garawad, R., Sultan, S., & Singh, H. (2022). *Technical*

581 *Manual: Management Effectiveness Evaluation (MEE) of Tiger Reserves in India*. National

582 Tiger Conservation Authority, Government of India.

583 [https://ntca.gov.in/assets/uploads/Reports/MEE/MEE\\_Technical\\_Manual\\_2022.pdf](https://ntca.gov.in/assets/uploads/Reports/MEE/MEE_Technical_Manual_2022.pdf)

584 68. Yadav, S., Tiwari, V., Mallick, A., Garawad, R., Talukdar, G., Sultan, S., Ansari, N.,

585 Banerjee, K., & Das, A. (2023). Management Effectiveness Evaluation of Tiger Reserves in

586 India, 2022 (Fifth Cycle), Summary Report. Wildlife Institute of India and National Tiger

587 Conservation Authority, Government of India.

588 [https://ntca.gov.in/assets/uploads/Reports/MEE/MEE\\_2022\\_summary\\_Report.pdf](https://ntca.gov.in/assets/uploads/Reports/MEE/MEE_2022_summary_Report.pdf)