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Managing Forest Fires in a Changing Climate

Abinash Mohanty and Vidur Mithal

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Image: iStock

Executive summary

There is no denying that in a warming and increasingly changing climate, forest fires are likely to intensify at an unprecedented scale, disrupting the ecological and socio-economic fabric of the country. Globally, fires are used as a forest management tool; however, rapid changes in climate and meteorological variables (high temperatures, inadequate precipitation, and wind speed anomalies) are fanning forest fires across the globe and in India as well (FAO 2020). Indian forests have the potential to sequester an additional 3 billion tonnes of CO2 equivalent by 2030 and ensure livelihoods for 22 per cent of the population (275 million) who rely on forests for their sustenance (Sharma 2018). India as part of the Bonn Challenge at the Conference of the Parties (COP) 15 committed to restoring 13 million hectares of its degraded forests by 2020, and an additional 8 million hectares by 2030 – which was enhanced to 26 million hectares in 2019 (PIB 2019).

There is plenty of scope to improve the management of forests – primarily to protect against the impacts of climate change, increase in the incidents of forest fires, deforestation, and forest diversions, among others. **About 36 per cent of forest cover in India falls under extreme, very high, high, and moderate forest fire–prone zones (FSI 2019)**.

Our study presents a micro-level assessment of forest fires by identifying the states most vulnerable to high-intensity forest fires and their district hotspots while taking into consideration the warming and varying climate. The study also investigates the impact of forest fires on local air pollution.

We use multi-decadal (2000–09|2010–19) spatio-temporal analysis to identify the high-intensity forest fire vulnerable states and their correlation with the varying microclimate.

The study argues that a comprehensive assessment for forest fires by integrating climatological scenarios at a localised level can help mitigate forest fires better. Our analysis suggests that there has been a 10-fold increase in forest fire incidences in the last two decades, whereas the total forest cover (TFC) has only increased by 1.12 per cent. Our analysis further suggests that tropical moist deciduous forests, followed by tropical dry deciduous forests, are most vulnerable to forest fires.

India is 2nd most vulnerable country in the global south to forest fires

Reddy et al. 2019

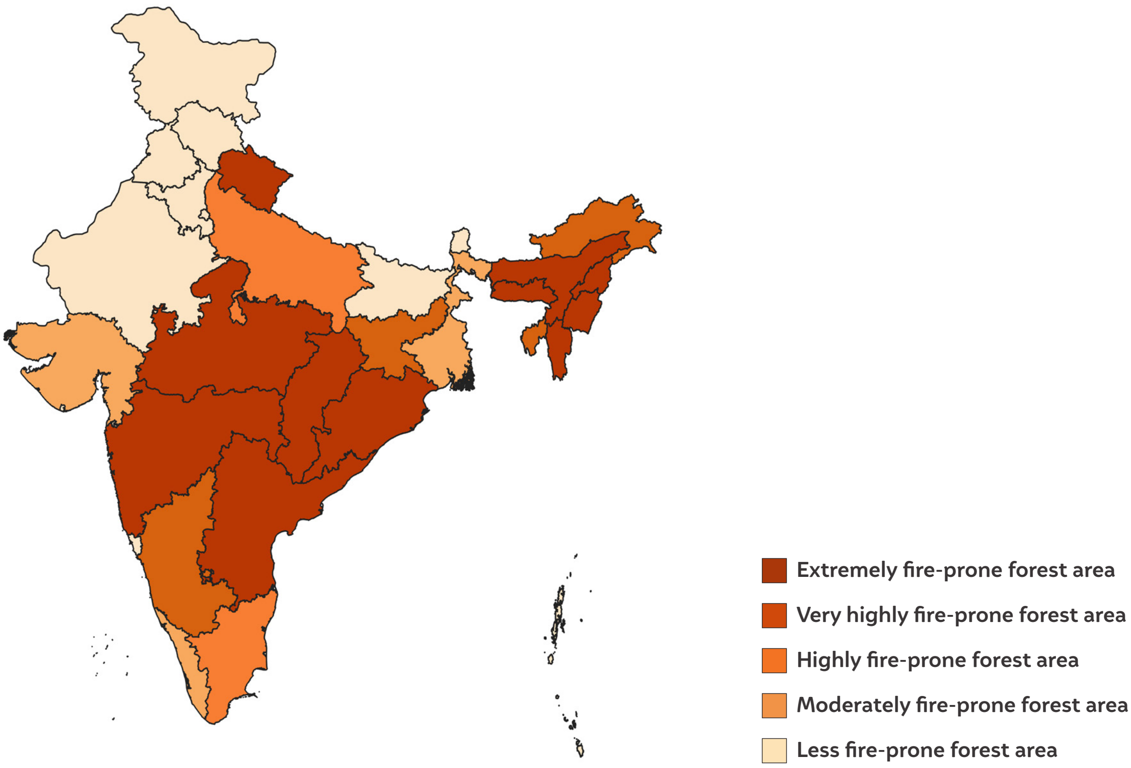
There has been a 10-fold increase in forest fire incidences in the last two decades, whereas the TFC has increased by 1.12%

CEEW analysis

Economic loss due to forest degradation is pegged at INR 1.74 lakh crore annually

MoEFCC, 2018

Figure ES1 More than 62% of Indian states are prone to high-intensity forest fire events (2000–19)



Source: Authors' analysis

Note: The base map shapefile is based on India's 2011 Census and, therefore, does not represent current states / UTs boundaries.

A. More than 30 per cent of Indian districts are hotspots for extreme forest fires

Our study finds that more than 30 per cent of all Indian districts, home to more than 275 million people, are extreme forest fire hotspots. Andhra Pradesh, Odisha, Maharashtra, Madhya Pradesh, Chhattisgarh, Uttarakhand, Telangana, and the north-eastern region (NER) states – except for Sikkim – are prone to high-intensity forest fire events. In the decade 2000–09, more than 58 per cent of Indian states were exposed to high-intensity forest fire events; among these states, 34 per cent were exposed to extreme forest fires; 13 per cent to very high intensity; and 10 per cent to high intensity forest fires, respectively.

Similarly, in the decade 2010-19, more than 65 per cent of states are exposed to high-intensity forest fire events, out of which 41 per cent are exposed to extreme forest fires, 13 per cent to very high, and 10 per cent to high forest fires, respectively. Further, table ES1 represents the forest fire hotspot states and districts based on our multi-decadal analysis (2000-09 | 2010-19).

Table ES1 Forest fire hotspot states and districts in order of proneness (highest to lowest)

Decade(s)	State hotspots	District hotspots
2000–19	Andhra Pradesh, Assam, Chhattisgarh, Odisha, Maharashtra, Madhya Pradesh, Manipur, Mizoram, Nagaland, Uttarakhand	Dima Hasao, Lunglei, Lawngtlai, Mamit, Harda, Jabalpur, Hoshangabad, Narayanpur, Udham Singh Nagar, Kandhamal, Garhchiroli

Source: Authors' analysis

B. 89 per cent of the forest fire extreme hotspot districts are located in drought hotspot regions

We performed a spatio-temporal analysis to map the forest fire hotspots on a downscaled Köppen classification of climate zones.[1] To understand the correlation between forest fire hotspots and varying microclimates, we use the base-level microclimate zone variation maps from Mohanty's (2020) microclimate zone analysis to derive an understanding of forest fire incidents across different microclimate zones. Our analysis suggests that most forest fire incidences are occurring across districts that are drought hotspots or are increasingly showing a swapping trend (traditional flood-prone areas becoming drought-prone). Further, this confirms that drought or drought-like conditions are marked by increased dry spells, which are consequently intensifying forest fires. Kandhamal (Odisha), Sheopur (Madhya Pradesh), Udham Singh Nagar (Uttarakhand), and East Godavari (Andhra Pradesh) are some of the forest fire hotspot districts that are also showing a swapping trend from flood to drought. Figure 5 maps the extreme forest fire–prone areas across varying microclimate zones. The forest fire district hotspots are primarily located in the Cwa[2], Bsh[3], Am[4], and Aw[5] climate zones. More than 79 per cent of the forest fire hotspots lie in the Cwa and Aw climate zones.

C. Onset of the fire season results in an increase in aerosol optical depth (AOD)

We also investigated the impact of changing forest fire patterns on local air pollution. Looking at the values for aerosol optical depth (AOD), we find that the onset of the fire season results in an increase in AOD, indicating higher levels of hazardous particulates in the atmosphere. This trend is observed for all the leading forest fire hotspots except Harda, Madhya Pradesh, wherein several factors may obscure results from this analysis. We also found the trend to be weaker in 2020, possibly owing to relatively fewer fires in that year and an above-average 2019 monsoon.

D. Improving forest-fire management

We recommend applying the principles of risk assessment and acknowledging forest fires as a chronic hazard at the core of India's strategy.

1. A microclimate is a local set of atmospheric conditions that differ from those of surrounding areas. A microclimactic zone (MCZ) refers to a change in climate variables, like temperature, precipitation, etc., leading to effects like UHIs, cloudbursts, hailstorms, and storm surges.
2. Cwa zones have at least ten times as much rain in the wettest month of summer than in the driest month of winter.
3. Bsh climates tend to have hot – sometimes extremely hot – summers and warm to cool winters, with some to minimal precipitation.
4. Am climate zones tend to have precipitation in driest month less than 60 mm but equal to or greater than 100 – (r/25).
5. Aw climates have a pronounced dry season, with the driest month having precipitation of less than 60 mm.

Our recommendations to climate-proof forests are as follows:

1. **Recognise forest fires as a disaster type and integrate them into national, sub-national and local disaster management plans**: The *National Plan on Forest Fires* was launched by the Government of India in 2018 under the flagship *National Afforestation Programme*. This plan touches upon a wide range of activities, but financial constraints and operational dynamism remains a challenge. Forest fires should be recognised as a disaster type under the NDMA act. The recognition will enhance and strengthen the *National Plan on Forest Fires* by improving its financial allocation and through the creation of a cadre of trained forest firefighters under the National Disaster Response Force (NDRF) and State Disaster Response Force (SDRF).

2. **Develop a forest fire-only alert system**: Currently, Forest Survey of India (FSI) and National Remote Sensing Centre (NRSC) use MODIS and Suomi NPP VIIRS information for near real-time monitoring of forest fires which does not segregate forest fires from other fires such as waste burning and crop burning. Hence, ground validation takes time and the scope for misinformation increases. As a first step, a forest fire ONLY alert system needs to be developed that can provide real-time impact-based alerts.

3. **Enhance adaptive capacity**: Capacity-building initiatives targeted at district administrations and forest-dependent communities can avert the extent of loss and damage due to forest fires. Training on high technology-focused equipment (like drones) and nature-based modules such as creating effective forest fire lines can effectively mitigate the spread of forest fires.

4. **Provide clean air shelters**: The state government/ state forest departments (SFDs) should repurpose public buildings like government schools and community halls by fitting them with clean air solutions – like air filters – to create clean air shelters for communities worst impacted by fires and smoke from forest fires.

1. Introduction

1.1 Forests and forest fires in India

Globally, forests occupy 31 per cent of the total land area (4.06 billion hectares) as per 2020 estimates (FAO 2020). Indian forests contribute 2 per cent to the global tally with around 72.16 million hectares of TFC. On the contrary, the annual global loss of forests due to deforestation is estimated at 64 million hectares, which is equivalent to the size of the total geographical area under United Kingdom. Similarly, India is losing 1.6 million hectares of forests annually, roughly twice the size of Andaman and Nicobar Islands (Kresek and Duraisami 2020). The scale of loss is further supplemented with recurrent forest fires in the recent decades.

The extent of forests in India is recorded as 'forest cover'[6] and 'recorded forest area' by the Forest Survey of India (FSI). At the Conference of Parties (COP) in 2015, India – as part of the Bonn challenge[7] – enhanced its commitment to restoring 26 million hectares of its degraded forests by 2030; which will increase India's total forest area by around 36 per cent (PIB 2019).

Indian forests have the potential to sequester an additional 3 billion tonnes of CO_2e by 2030 and ensure sustained sustenance services for 22 per cent of its dependent population (275 million) (TERI 2017). While forest cover is increasing at an incremental rate, its rate of degradation is accelerating and the degradation loss will cost India INR 1.74 lakh crore per annum (MoEFCC 2018). There is enough empirical evidence to show that forests render both climate adaptation and mitigation co-benefits. While India's forest cover, including its tree cover, has increased by 3 per cent in the last decade (2011–2019) (FSI 2019), there is a need for greater proactivity in managing forests considering the increased threats they face – primarily due to

> **Forest fires should be acknowledged as a chronic hazard at the core of India's disaster management strategy.**

6. Forest cover includes all patches of land with a tree canopy density of more than ten per cent and more than one hectare in area, irrespective of land use, ownership, and species of trees.
7. The Bonn Challenge is a global goal to restore 150 million hectares of degraded and deforested landscapes by 2020 and 350 million hectares by 2030.

Most of the forest fire incidences are occurring across districts that are drought hotspots or are increasingly showing a swapping trend (traditional flood-prone areas becoming drought-prone).

climate change, increase in the incidence of forest fires, deforestation, and forest diversions, among others. Forests are subject to the stated disturbances, which adversely affect their health and affect a range of ecosystem and socio-economic services. Traditionally, fire is quite commonly used by forest-dependent populations to manage forests, but what is significantly intensifying incidences of forest fires is climate change (FAO 2020).

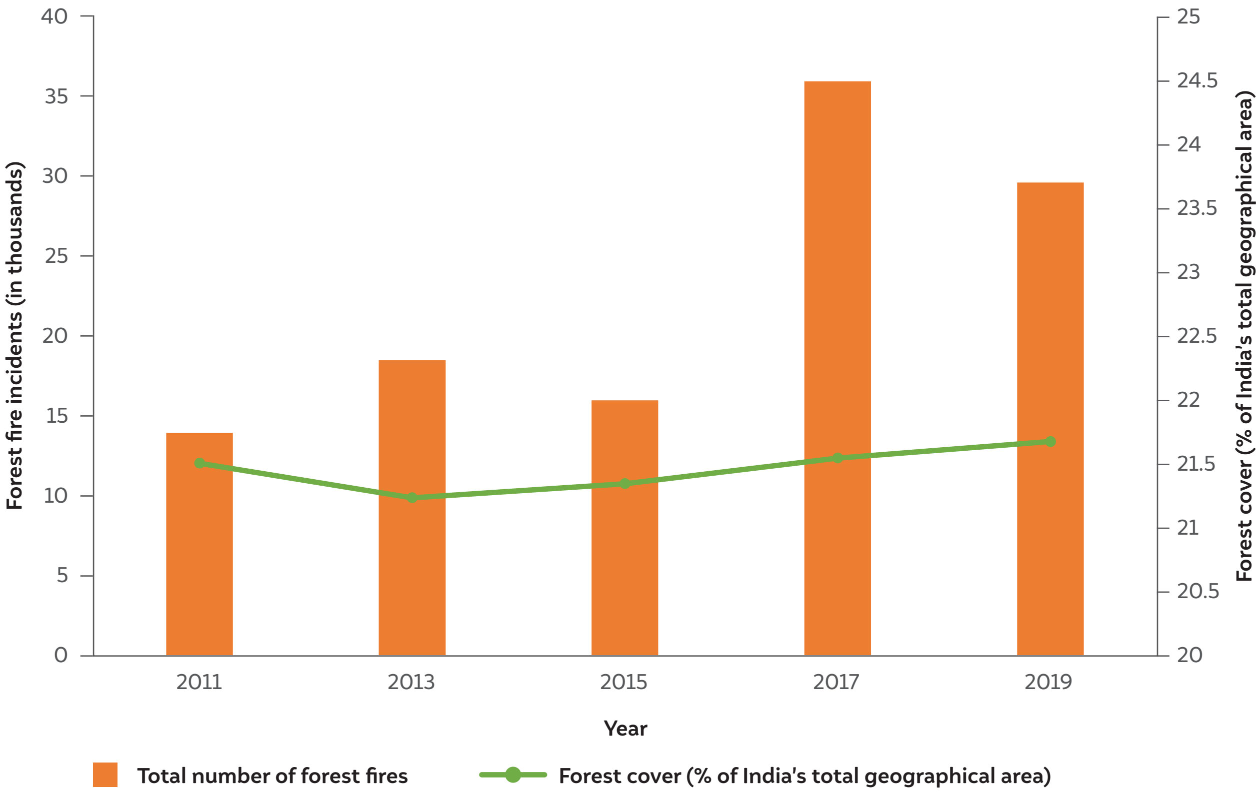
From a governance standpoint, forest fires are under the prerogative of the Ministry of Environment, Forest and Climate Change (MoEFCC) and the SFDs at a sub-national level. Forest fire management is under the purview of the National Afforestation Programme (NAP) and Forest Fire Prevention and Management Scheme. In 2018, the MoEFCC launched the Nation Action Plan on Forest Fires (NAPFF). The NAPFF aims to enable and empower forest fringe communities to reduce forest fire incidences but it still lacks a budgetary allocation for its implementation and is cross-allocated through the Compensatory Afforestation Fund Management and Planning Authority (CAMPA) (FSI 2019).

Disturbances caused by forest fires are a global concern, and millions of dollars are being pledged to restore and fire-proof forests. Forest fires pose a serious threat to biodiversity and significantly contribute to air pollution and GHG emissions (Reddy et al. 2019); further, forest fires cause economic losses and the loss of soil nutrients and moisture (Parashar and Biswas 2003). Chapter 3 provides an empirical assessment of forest fires vis-à-vis their contribution to localised air pollution. Some recent devastating forest fire incidents in India are the fires in Odisha, Simlipal forest range (2021), Uttarakhand, Pauri Garhwal (2021), and Madhya Pradesh, Bandhavgarh Tiger Reserve (2021), among others, caused great damage. Globally, in 2001–2018, more than 7.20 billion hectares of forests were burnt, estimated to be about 400 million hectares per year (Artes et al. 2019). The rate of occurrence of forest fire incidences has also exponentially surged in the last decade (2011–2019). Beyond India, globally some of the major forest fire incidences were the Amazon Rainforest fires (2020), the Arctic fires (2019), and the Australian forest fires (2019–20). According to the FSI, the national forest cover – excluding tree cover – has increased by 0.17 per cent in the last decade, but the number of forest fire incidences has increased by about 52 per cent (Figure 1) (FSI 2019). Clearly, forests of India are being impacted by forest fires at an erratic scale, disrupting the ecological and socio-economic fabric on various fronts. Climatic changes are further worsening the impacts and prolonging these single and multiple forest fire incidences. Various studies have suggested that climate change is contributing adversely to the intensity of forest fires (measured by area burnt) and their frequency (Melillo et al. 2014). A warmer climate primarily leads to an increased[8] dry season and dry spells, making the land and soil drier and more vulnerable to forest fires. Chapter 3 shows how areas witnessing drought and drought-like conditions are more vulnerable to extreme forest fires.

Image: Quarrie Photography | Jeff Walsh | Cass Hodge

8. A warmer climate leads to a longer dry season thus a longer fire season.

Figure 1 While the TFC of India has increased by only 0.17%, the frequency of forest fire incidents has increased by 52%



Source: FSI (2019)

It is evident that climate change is causing fire-favourable weather – hot temperatures, low humidity, and increased dry spells (Garnaut 2008). While forests can mitigate and reverse climate change impacts, there is no denying that climate-proofing forests is the need of the hour. In recent decades, the FSI has made significant progress in tracking and monitoring forest fires. It is currently using satellite-based remote sensing technology to identify, monitor, and manage forest fires (FSI 2019). However, the improved forest fire system does not segregate forests fires from crop burning and waste burning, among others. Hence, a strategic response mechanism is lacking. Another aspect to consider is the population dependent on forests, which often uses fire as a tool to manage forests (Thekaekara et al. 2017). However, this can often act as an ignition event for such large-scale devastation, due to weather conditions created by climate change. There are 16 major categories of forest types in India, of which tropical moist and deciduous forests have the largest share, followed by tropical evergreen forests, and the Himalayan moist temperate forests (FSI 2019).

Globally, 197 countries are committed to the Paris Agreement, which reiterates the need for action to limit global warming to well below 2°C. Presently, the climatic extremes we see now are a result of a 1°C rise (Ebi et al. 2018). In India, current climate extremes are a result of a 0.6°C rise, and as the temperature increases, more and more climatic and meteorological disruptions will be witnessed (Mohanty 2020), along with an increase in associated catastrophes like forest fires. As the increasing frequency of forest fires in recent decades is a point of concern for countries, this paper generates empirical evidence on understanding the role of climate change in intensifying forest fires. We provide an empirical assessment of forest fire linkages across climatic and micro-climatic zones by identifying the states vulnerable to forest fires and their district hotspots through geospatial temporal analysis. The paper also attempts to understand the impact of forest fires on air pollution. Safeguarding the forests and increasing TFC is pivotal in achieving India's NDC and Bonn targets, given India is extremely vulnerable to climate change. As forest fires are going to intensify in a fast-changing climate scenario, managing forest fires and climate-proofing forests and forest-dependent populations should be a national imperative.

1.2 Research questions

While many studies have focused on understanding the pathology of forest fires across various ecological and socio-economic scenarios, empirical studies on its links to climate impacts remain a key research gap. Although gridded forest fire data is available for recent decades, segregated forest fire data remains a challenge, and a climate change impact–oriented study is yet to be undertaken. The study attempts to generate empirical evidence through spatial and temporal analysis to map forest fire vulnerable zones, thereby mapping district hotspots in a changing climate scenario.

- **What is the pattern and frequency of forest fires over the last two decades, and what are the state- and district-level hotspots?**

  Various studies have highlighted the importance of understanding the pattern, frequency, and intensity of forest fires through spatial and temporal mapping, but they often fail to provide a continuous multi-decadal analysis and, more importantly, the correlation between forest fires and the changing climate scenario. Globally and in India, the reporting of forest fire events has always been an issue. After 2004, the FSI – through moderate-resolution imaging spectroradiometer (MODIS) sensor data – has implemented near real-time monitoring of forest fires. The limitation to MODIS data remains, as it includes all kinds of fire incidences, i.e., forest fires, crop burning, and waste burning, among others. This study intends to understand the pattern, frequency, and intensity of forest fires over the last two decades by developing a forest-fire only catalogue as a first step and identifying the state-level exposure zones and their district hotspots. Since district-level forest fire–only incidence data are not available for multiple decades, we have considered the MODIS data to identify district hotspots.

- **How has the frequency and intensity of forest fires changed across varying micro-climatic conditions, and how prominent is it across climate extreme event hotspots?**

  Evidence from the literature suggests that the warming climate has increased the severity of forest fires across the globe, but empirical evidence on how it is interlinked is still being established. The study intends to understand relation between microclimate variations and forest fire vulnerability. As microclimate zones are shifting across Indian districts due to climate change (Mohanty 2020), how it is intensifying forest fire incidences is an important point of investigation. Further, the study also examines which extreme events hotspots are exposed to forest fires so that disaster response mechanisms can be better prepared to tackle them.

- **How do forest fires impact local air quality?**

  Forest fires are known to impact both local and regional air quality significantly (Singh 2016; Sharma 2021; Gupta et al. 2018; Yarragunta et al. 2020) and have significant adverse health impacts – particularly severe respiratory disease (Finlay et al. 2012). Forest fires emit various gaseous and particulate pollutants, including CO, NO_2, CO_2, PM_{10}, $PM_{2.5}$, and benzene (Bytnerowicz et al. 2009). Regions such as California in the US that are prone to forest fires have reported a 220 per cent increase in $PM_{2.5}$ concentration in the vicinity of fire sites (Meo et al. 2021). Given that most of India's air quality monitoring stations are in urban areas, there is zero to limited data on air quality in regions impacted by forest fires. To address this gap, we use satellite-derived products to assess the effect of forest fires on local air quality.

2. Methodology

A comprehensive hazard assessment is the first step in performing a risk assessment (IPCC 2018). While many studies have been conducted to identify the characteristics of forest fires, they are still not considered a hazard and systemic exposure assessment with respect to specific regions is still lacking (Reddy et al. 2018). Our multi-decadal micro-level exposure assessment focuses on generating empirical evidence on the exposure of sub-national regions to forest fires, identifying their district-level hotspots, and examining how micro-climatic variations are intensifying the scale of forest fires. The study also tries to identify the air pollution load due to forest fires. Any climatologically or meteorologically oriented study is dependent on the quality and quantity of data.

There are three main components to our methodological approach:

i) Development of a forest fire events roster on a multi-decadal time scale (2000–2019) and thereby develop a gridded exposure sheet of forest fire events using MODIS data to identify the district hotspots in forest fire–prone states.

ii) Geospatial analysis of forest fire–exposed regions using coarse-grain resolution temporal maps to identify micro-climatic variations.

iii) Mapping the impact of forest fires on local air quality.

2.1 Development of a forest fires roster and gridded exposure sheet

We conceptualise exposure to forest fires in terms of their frequency in a particular grid as categorised by FSI. We coupled information from global data sets like Global Forest Resources Assessment (GFRA) with national-level reporting of forest fire events from the Press Information Bureau (PIB), Ministry of Environment, Forest and Climate Change (MoEFCC), Ministry of Finance, Ministry of Statistics and Programme Implementation (MoSPI), Forest Survey of India (FSI), and other literature for developing the forest fires roster across two decades (2000–09 and 2010–19). In India, the FSI uses MODIS information to report and track forest fire incidences. However, MODIS does not segregate between forest fires, waste burning, and crop burning; rather, it considers all of them for forest fire incidence reporting. It is important to have a forest fire–only roster to do any spatial or temporal investigations. The main objective of the forest fire roster is to perform multi-decadal analyses of forest fire events at a state level. Learnings from the literature suggest that spatio-temporal analyses can shed light on a region's proneness to forest fire incidences (Reddy et al 2019; Naranjo et al. 2018). To maintain a uniform categorisation of forest fire incidences, we followed the FSI category of identification of forest fires (Figure 3). We developed a state-level gridded exposure sheet using the FSI categorisation at 5 x 5 km resolution based on the number of yearly forest fire incidences. Since there is complexity and non-linearity at a district level in a particular state with reference to forest fires incidence reporting, we used FSI and MODIS data to identify the district-level forest fire hotspots.

We procured the base maps for the pentad decadal analysis from ISRO at 25 km resolution. For the temporal analysis, we used coarse grain resolution, and for the climate zone analysis, we derived the base Köppen-Geiger classification from the NASA Earth database.

The gridded exposure data sheet was developed using QGIS, which was further used for re-gridding and clipping micro-climatic zones enumerated in the section below to understand microclimate zone variations across the forest fire–exposed regions and their district-level hotspots.

2.2 Geospatial analysis of regions exposed to forest fires using coarse-grain resolution temporal maps to identify micro-climatic variations

We use baseline administrative boundary shape files from the Indian Space Research Organisation's (ISRO) National Remote Sensing Centre (NRSC) to develop state-level exposure and district-level hotspot maps. To analyse microclimatic zone variations, we derived climatic zone classification base maps from global reanalysis shape files modelled by National Oceanic and Atmospheric Administration (NOAA) (Becke et al. 2018) and clipped using QGIS 3.10. We did a multi-decadal geospatial analysis of the gridded exposure sheet based the frequency of forest fires (no. of forest

Table 1 Forest fire proneness criteria

Category	Range
Extremely fire-prone forest area	Average frequency of forest fires ≥4 in a grid per year
Very highly fire-prone forest area	Average frequency of forest fires (≥ 2 and <4) in a grid per year
Highly fire-prone forest area	Average frequency of forest fires (≥ 1 and <2) in grid per year
Moderately fire-prone forest area	Average frequency of forest fires (≥ 0.5 and <1) in grid per year
Less fire-prone forest area	Average frequency of forest fires (< 0.5) in grid per year

Source: Authors' compilation based on FSI, 2019.

> **According to the Köppen classification, India has six climatic zones: tropical humid, dry, warm, temperate, cold, cold snow forest, and highlands.**

fire incidences/grid/in a particular year), the intensity of forest fires (burnt areas), and the number of districts affected in particular states. Gridded data requires consistency and coherent data inputs without outliers and missing information/values. Some preparatory spatial jobs like clipping, masking, and raster-based maths were performed in a desktop environment. We performed spatial scale analysis of the decadal and exposure maps using QGIS to derive empirical evidence on micro-climatic variations vis-à-vis forest fire exposure of regions. To assess the intertemporal distribution of forest fire events across regions, the same methodical approach was followed.

2.3 Mapping the impact of forest fires on local air quality

Our spatio-temporal analysis suggests that Lunglei in Mizoram, Kandhamal in Odisha, Garhchiroli in Maharashtra, Harda in Madhya Pradesh, and Dima Hasao in Assam are some of the leading forest fire hotspots in the country. We sought to examine how forest fire incidences in these areas have impacted the local air quality in the last five years. However, we find that none of these districts houses a real-time air quality monitor.

Given the absence of air quality data from these regions, we use AOD to assess pollution levels in these regions for the period coinciding with the forest fire burning window (February–June).[9] AOD is a measure of haziness in the atmosphere and is widely used as a proxy for particulate matter concentrations. An AOD of less than 0.1 indicates a clear sky with maximum visibility, whereas a value greater than 1 indicates hazy conditions (Kumar, Chu, and Foster 2007; Krishna et al. 2019; Maheshwarkar and Raman 2021; Xu and Zhang 2020). We used Google Earth Engine (GEE) to access the MODIS Terra and Aqua combined Multi-angle Implementation of Atmospheric Correction (MAIAC) Land AOD product produced daily at 1-km resolution (Lyapustin and Wang 2021) Gorelick et al. 2017). Data on open fire events detected by VIIRS was accessed via the NASA Fire Information for Resource Management System (FIRMS) portal for forest fires.

2.4 Scope and limitations

FSI classifies forest fires in India, but internationally, no consensus is available on the classification of forest fire incidences to map exposure and vulnerability levels. The use of MODIS data has its own limitations, as it does not consider forest fire events only, and ground validation remains a challenge. Since trends of forest fire incidence are non-linear and complex, understanding its variation across varying temperatures requires a detailed climatological analysis, which is beyond the scope of this study. In the absence of uniform granular climatological data, we intend to separately carry out a climatological analysis to further understand the micro-correlation between forest fires and microclimate variables, which can be regarded as a limitation. To maintain uniformity, we have considered Government of India–reported sources for developing the forest fire rosters; however, some independent researchers have highlighted additional reporting of forest fire events, although they are few in number – especially for 2000–04. The forest fire events considered for the catalogue are high-intensity forest fires and do not consider the net loss of forests due to forest fires. We did not include a micro-level analysis of the forest fire duration in our analysis due to data limitations. To understand the impact of forest fires on local air quality, we analysed changes in AOD. It is worth cautioning that variations in AOD is only indicative of variations in particulate matter levels and is not a direct measure of particulate concentrations. The rise in AOD levels reflects the surge in particulates from all polluting sources including forest fires.

3. Results and discussion

While the climate is changing fast, forests are the most effective mitigation tool to reverse climate change impacts and they also have mitigation and adaptation co-benefits. Globally, India is the seventh-most climate-vulnerable country in the world (Germanwatch 2021), and more than 75 per cent of its districts are extreme

9. We do not use Sentinel 5P datasets on CO, NOx, etc. due to the unavailability of the data prior to 2017 or 2018, depending on the product. AOD products are available for a longer duration, allowing more robust analysis.

events hotspots (Mohanty, 2020). While forest cover in India has increased by 0.17 per cent, the number of forest fire incidents has increased by more than 52 per cent (FSI 2019). Forest fires remain one of the most pressing disturbances that are increasing in frequency, intensity, and burnt area. According to the FSI, some of the associated damages of forest fires are soil erosion, landslides, loss in forest produce, loss of regeneration, and habitat degradation (FSI 2017). The FSI also acknowledges that incidences of forest fires are related to climate change, but not many studies at the India-level have been undertaken. Various literature has stated that climate change is directly linked to making forests more inflammable, and, as a result, the frequency and intensity of forest fires are exponentially increasing (Flanningan et al. 2008). As climate change is driving the incidence of forest fires to record highs, technology, policy, capacity, and community-led awareness gaps remain at the centre of this surge.

The forest fire alert system has undergone significant changes and improvements since its inception in 2004, forest fire incidences are still increasing due to various climatic, socio-economic, and capacity-led gaps. India's commitment to restore 26 million hectares of degraded forest by 2030 is currently looks far from reality if forest fire incidences continues to surge exponentially.[10] It is important to understand the state of forest fires and how climate change is exacerbating the impacts by intensifying forest fires and hindering the development of effective response mechanisms. The following sections provide empirical evidence on the forest fire exposure of regions and the impact of climate change over the last 20 years. Section 3.3 also enumerates the state of forest fires and their contribution to localised air pollution.

Globally, India is the only country in the world whose forest cover has increased across all categories (very, moderately dense, and open forests) (FSI 2019). While these trends are satisfactory, India is far behind its committed target of converting 33 per cent of its total geographical area to forest cover. According to India's Nationally Determined Contributions (NDCs), it has committed to creating a cumulative carbon sink of 2.5–3 billion tonnes of CO_2 equivalent by 2030 (PIB 2015). The FSI estimates that the current carbon stock in forests is about 7124.6 million tonnes. Forests are the lifeline of India's environmental health, but what is worrisome is its rate of deforestation.[11] Various studies have ranked forest fires as major forest disturbances (Kumari et al. 2019). We performed a multi-decadal spatio-temporal analysis to understand the patterns, frequency, and intensity of forest fires and identify vulnerable states and their district hotspots in a changing climate scenario.

More than 65% of the states are exposed to high-intensity forest fire events.

Sections 3.1 and 3.2 discuss the patterns, intensity, and frequency of forest fires through a multi-decadal spatio-temporal analysis by identifying the vulnerable states and their district hotspots. Further, Section 3.3 discusses the complexity and non-linear patterns of forest fires with respect to micro-climatic variations; and section 3.4 discusses the impact of forest fires on local air quality.

3.1 Multi-decadal analysis of forest fires in India

As established earlier, our learnings from the literature suggest that forest fire incidences are a major cause for concern in India. India ranks second among the countries of the global south in terms of proneness to forest fires, followed by Bangladesh (Reddy et al. 2019). Our analysis of extreme forest events suggests that, since 2003, the number of forest fire incidents have increased exponentially. However, the trend of forest fire incidences is non-linear and abrupt with respect to its frequency. The literature suggests that varying microclimate lead to increased spring temperatures and low precipitation levels, which contribute significantly to the abrupt trends in forest fires predominantly around March–May (Ahmad et al. 2018). Figure 2 illustrates the forest fire–prone states of India characterised as per the FSI's category of i) extremely fire-prone forest area, ii) very highly fire-prone forest area, iii) highly fire-prone forest area, iv) moderately fire-prone forest area, and v) less fire-prone forest area.

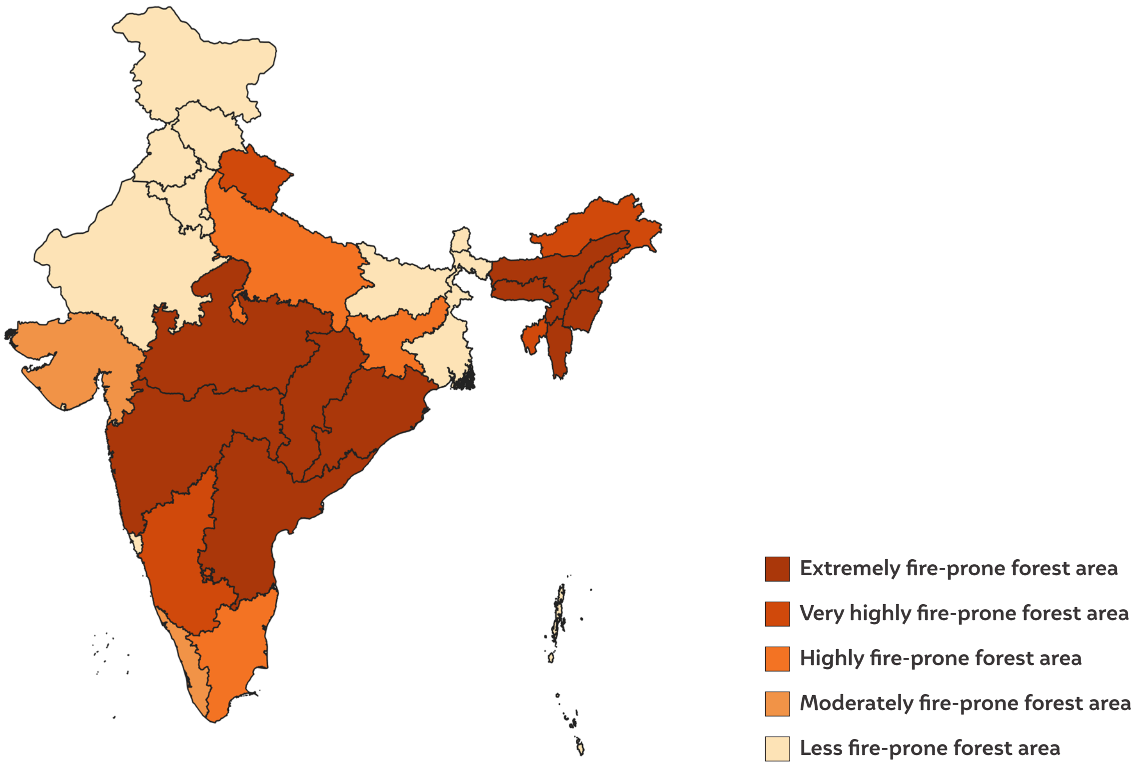
10. India joined the Bonn Challenge in 2015 with a pledge to restore 21 mha of degraded and deforested land. This was raised to a target of 26 mha by 2030 during the United Nations Convention on Combating Desertification Conference held in Delhi in September 2019.

11. The UN Food and Agricultural Organization (FAO) defines deforestation as the conversion of forests to another land use or the long-term reduction of tree canopy cover below the 10 per cent threshold.

During 2000–09, more than 58 per cent of Indian states were exposed to high-intensity forest fire events; among these states, 34 per cent were exposed to extreme forest fires; 13 per cent to very high intensity; and 10 per cent to high intensity forest fires, respectively. Andhra Pradesh, Assam, Chhattisgarh, Odisha, Maharashtra, Madhya Pradesh, Manipur, Mizoram, and Nagaland were the extreme forest fire–prone states in the concerned decade. Table 2 enumerates the district hotspots of forest fires during 2000–09.

Learnings from the literature indicate that the frequency and intensity of forest fires have increased significantly in the last decade (2010–19); our analysis further validates the same. More than 65 per cent of states are exposed to high-intensity forest fire events, out of which 41 per cent are exposed to extreme forest fires, 13 per cent to very high, and 10 per cent to high forest fires, respectively (Figure 3). Andhra Pradesh, Assam, Chhattisgarh, Odisha, Maharashtra, Madhya Pradesh, Manipur, Mizoram, Nagaland, and Uttarakhand are the extreme forest fire–prone states. It is important to note that some of these states also have a very high TFC. Table 2 enumerates the district hotspots for forest fires in the decade 2010–19.

Figure 2 More than 58% of Indian states were exposed to high-intensity forest fire events during 2000-2009



Source: Authors' analysis

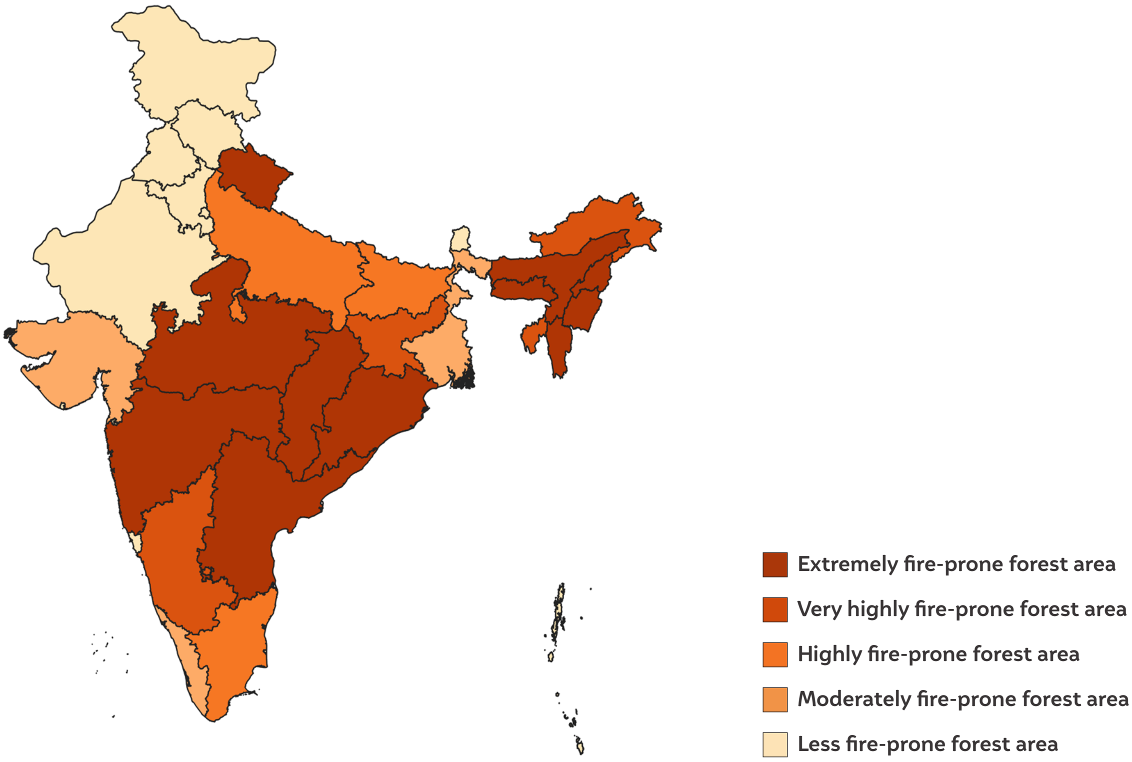
Note: The base map shapefile is based on India's 2011 Census and, therefore, does not represent current states / UTs boundaries.

Table 2 Decadal district forest fire hotspots in order of proneness (highest to lowest)

Decade	District hotspots (in order of proneness)
2000–09	Mizoram (Lunglei, Lawngtlai, Aizawl, Champhai), Manipur (Ukhrul), Assam (Karbi Anglong), Uttar Pradesh (Kheri - Lakhimpur), Maharashtra (Chandrapur, Garhchiroli), Odisha (Koraput)
2010–19	Assam (Dima Hasao), Manipur (Tamenglong), Mizoram (Lunglei, Aizawl, Champhai), Uttar Pradesh (Maharajganj), Uttarakhand (Nainital), Maharashtra (Garhchiroli, Ratnagiri), Madhya Pradesh (Narsimhapur)

Source: Authors' analysis

Figure 3 **Andhra Pradesh, Assam, Chhattisgarh, Odisha, Maharashtra, and Madhya Pradesh are the most vulnerable to forest fires during 2010–2019**



Source: Authors' analysis

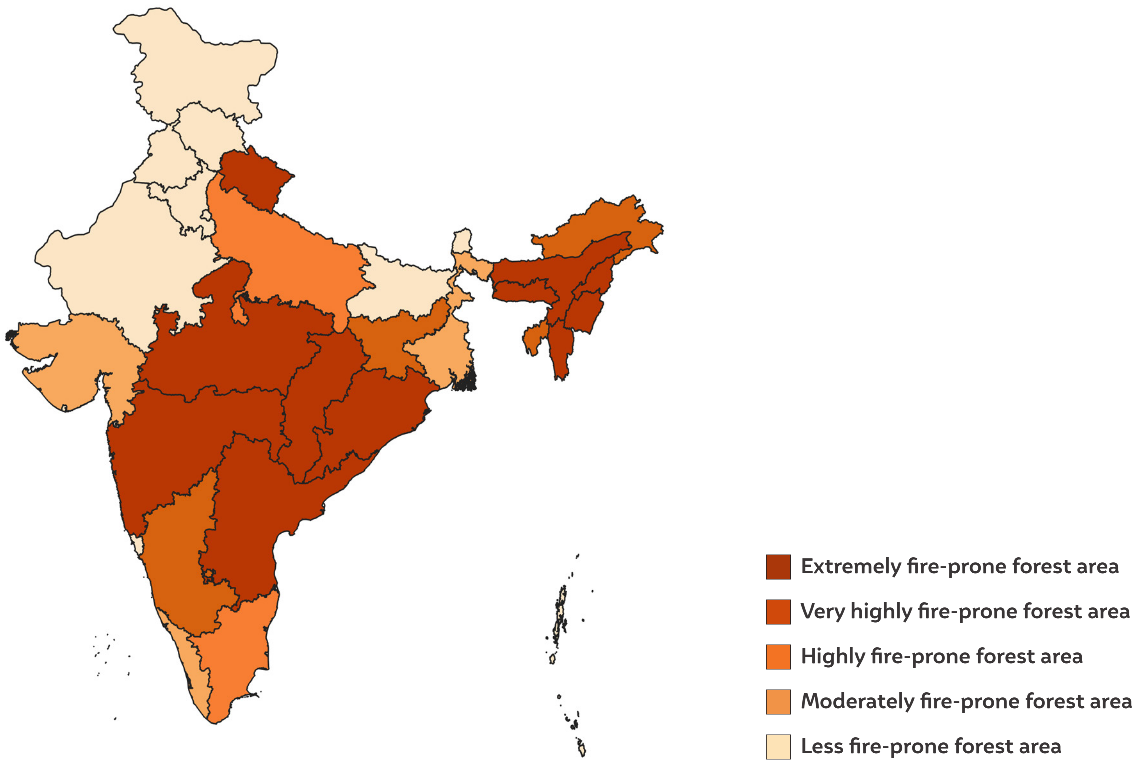
Note: The base map shapefile is based on India's 2011 Census and, therefore, does not represent current states / UTs boundaries.

3.2 State of forest fires in India

Our analysis suggests that more than 62 per cent of Indian states are prone to high-intensity forest fires. There has been a 10-fold increase in forest fire incidences in the last two decades, whereas the TFC has increased by 1.12 per cent (Figure 3). The statistics and empirical evidence clearly suggest that forests need renewed attention and a focus on improving their ecological health. About 36 per cent of forest cover in India falls under the category of extreme, very high, high, and moderate forest fire–prone zones (FSI 2019).

Image: iStock

Figure 4 More than 62% of Indian states are prone to high-intensity forest fire events (2000-2019)



Source: Authors' analysis

Note: The base map shapefile is based on India's 2011 Census and, therefore, does not represent current states / UTs boundaries.

More than 75 per cent of Indian districts are extreme climate event hotspots (CEEW 2020), while more than 30 per cent of districts are extreme forest fire hotspots. Our analysis suggests that Andhra Pradesh, Odisha, Maharashtra, Madhya Pradesh, Chhattisgarh, Uttarakhand, Telangana, and the north-eastern region (NER) states – except for Sikkim – are prone to high-intensity forest fire events.

Our analysis suggests that Mizoram has had the highest number of forest fire incidences in the last two decades, with more than 95 per cent of its districts being forest fire hotspots, which is validated by the findings in the FSI (2019). The district-level hotspots of Mizoram are Kolasib, Lawngtlai, Lunglei, Mamit, and Saiha, among others. Our analysis also suggests that most of the NER, including Arunachal Pradesh, Assam, Meghalaya, Mizoram, Nagaland, Manipur, and Tripura, barring Sikkim, are witnessing an increased frequency of forest fire incidences in recent decades; these findings are further validated by Chakrobarty et al. (2014). Further, within the NER, slash-and-burn agricultural practices like jhum agriculture are predominant and often play an active role in driving these fires. It is interesting to note that despite the NER being a rain-fed area, it is witnessing more forest fire incidences during increased dry spells across March–May and due to the muddled rainfall distribution pattern (Sangomla 2020).

Table 3 illustrates the extreme forest fire hotspot districts of India. In addition to the districts of Assam and Mizoram in the NER, the forest fire hotspots span across Madhya Pradesh, Uttarakhand, Chhattisgarh, and Odisha.

Table 3 Forest fire hotspot district in order of proneness (highest to lowest)

Decade(s)	District hotspots
2000–19	Dima Hasao (Assam), Lunglei (Mizoram), Lawngtlai (Mizoram), Mamit (Mizoram), Harda (Madhya Pradesh), Jabalpur (Madhya Pradesh), Hoshangabad (Madhya Pradesh), Narayanpur (Chhattisgarh), Udham Singh Nagar (Uttarakhand), Kandhamal (Odisha), Garhchiroli (Maharashtra)

Source: Authors' analysis

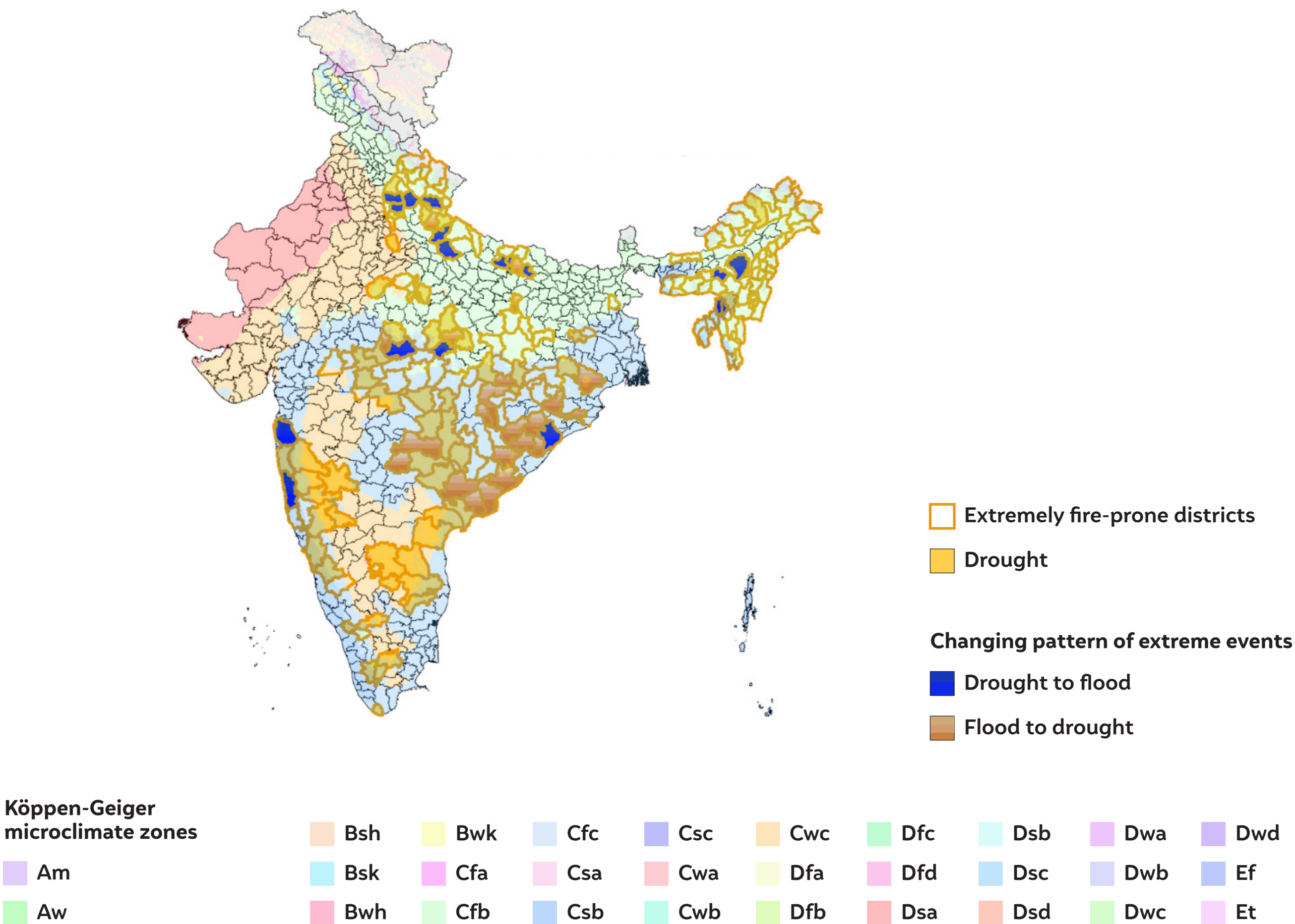
Section 3.3 correlates forest fires with micro-climatic variations and analyses the correlation between forest fire incidents across different micro-climatic zones. Our analysis suggests that primarily tropical moist deciduous forests, followed by tropical dry deciduous forests, are most vulnerable to forest fires. The forest fires occur primarily across these forest types in February–April (Firoz et al. 2018). Deciduous forests have a high composition of dry inflammable materials in the form of grass and leaf litter, which are sensitive to littering – and hence, the rate of forest fire incidence is high in these forest types; further, a more frequent dry spell increases the availability of dry inflammable materials. Our analysis suggests that forest fire frequency is highest across NER, followed by central India; the findings of which are validated in Reddy et al. (2019).

3.3 State of forest fires in a varying micro-climatic scenario

As enumerated in Chapter 2, we did a spatio-temporal analysis to map the forest fire hotspots over a downscaled Köppen classification of climate zones; the base-level climate zone varying attribute map was adopted from Mohanty (2020) to derive an understanding of forest fire incidents across different microclimate zones.

Various literature suggests that to understand climatic variations across different locations, Koppen–Geiger climate zone analysis can be undertaken (Beck et al. 2018). However, we use Köppen climate zones to understand the impact of the pattern of change in climate zones on forest fire incidence. India is divided primarily into six climatic zones with 15 sub-types; the characteristic features of these climate zones are detailed in Annexure 1. We have considered Köppen classification sub-types as the baseline reference for the variation in climate zones, using temporal re-analysis maps released by NASA in 2000. Our analysis suggests that most forest fire incidences are occurring across districts that are drought hotspots or are increasingly showing a swapping trend (traditional flood-prone areas becoming drought-prone).

Figure 5 Forest fire incidences vis-à-vis climatic zones

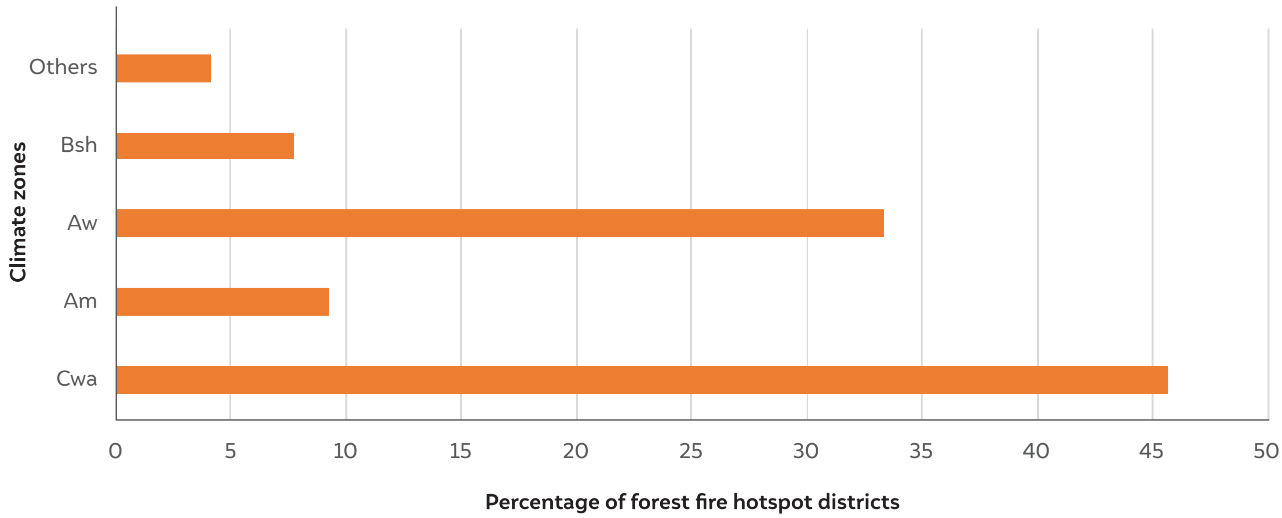


Source: Authors' analysis

Further, this confirms that drought or drought-like conditions are marked with increased dry spells, which in turn ignite the flames of forest fires. Figure 5 maps the extreme forest fire–prone areas across varying micro-climatic zones. More than 68 per cent of Indian districts witness extreme drought or drought-like conditions,[12] and 89 per cent of the forest fire extreme hotspot districts are located in these regions. Kandhamal, Sheopur, Udham Singh Nagar, and East Godavari are some of the forest fire hotspots that are also showing a swapping trend from flood to drought.

The forest fire district hotspots are primarily located in the Cwa,[13] Bsh,[14] Am,[15] and Aw[16] climate zone categories (Figure 5). More than 79 per cent of the forest fire hotspots lie in Cwa and Aw climate zones. The Cwa category of climate zones are characterised by distinct dry spells due to lesser precipitation where the mean daily temperature during warmer seasons lies between 30–38°C (Beck et al. 2018). Similarly, the Aw category of climate zones has an extended dry season with a mean maximum temperature of 35°C. The geospatial analysis implies that the microclimatic zones are swapping across districts; hence, with more erratic dry conditions, forests are becoming prone to forest fires. Increased forest fire incidents are seen in Cwa category districts that are swapping to the Aw and Am category, further validating that the microclimate is varying faster and making forests more prone to forest fires due to the larger spans of dry spells across certain months (February–April). A varying and warming microclimate and land-use surface changes lead to a greater increase in sea surface temperatures (SST) and land surface temperatures (LST). The varying LST and SST impacts the monsoonal anomalies across coastal regions and evidently, our analysis also suggests that coastal regions have increasingly become forest fire-prone.

Figure 6 **More than 79% of forest fire hotspot districts are in the Cwa/Aw category of climate zones**



Source: Authors' analysis

12. Meteorological drought is defined as the deficiency of precipitation from expected or normal levels over an extended period of time. Hydrological drought is defined as deficiencies in surface and subsurface water supplies, leading to a lack of water for normal and specific needs. Agricultural drought is usually triggered by meteorological and hydrological drought, and occurs when soil moisture and rainfall are inadequate during the crop growing season, causing extreme crop stress and wilting.
13. Cwa zones have at least ten times as much rain in the wettest month of summer than in the driest month of winter.
14. Bsh climates tend to have hot – sometimes extremely hot – summers and warm to cool winters, with some to minimal precipitation.
15. Am climate zones tend to have precipitation in driest month less than 60 mm but equal to or greater than 100 – (r/25).
16. Aw climates have a pronounced dry season, with the driest month having precipitation of less than 60 mm.

Learnings from the literature confirm that climate change is intensifying climatic and meteorological events and making them harsher, which is affecting forest health. However, a detailed climatological analysis will be required to derive the exact correlation between micro-temperature increases and forest fire incidence in hotspot districts. Through our study, enough empirical evidence has been generated to show that forest fires are triggered by a varying and warming climate. These findings imply that a more comprehensive forest-focused climatological and meteorological assessment can help in climate-proofing forests, which will help India mitigate climate change faster and achieve its NDC targets. Further, risk-informed forest management will help secure forests and their dependent, vulnerable populations from the impacts of prolonged forest fire events in a warming and varying climate.

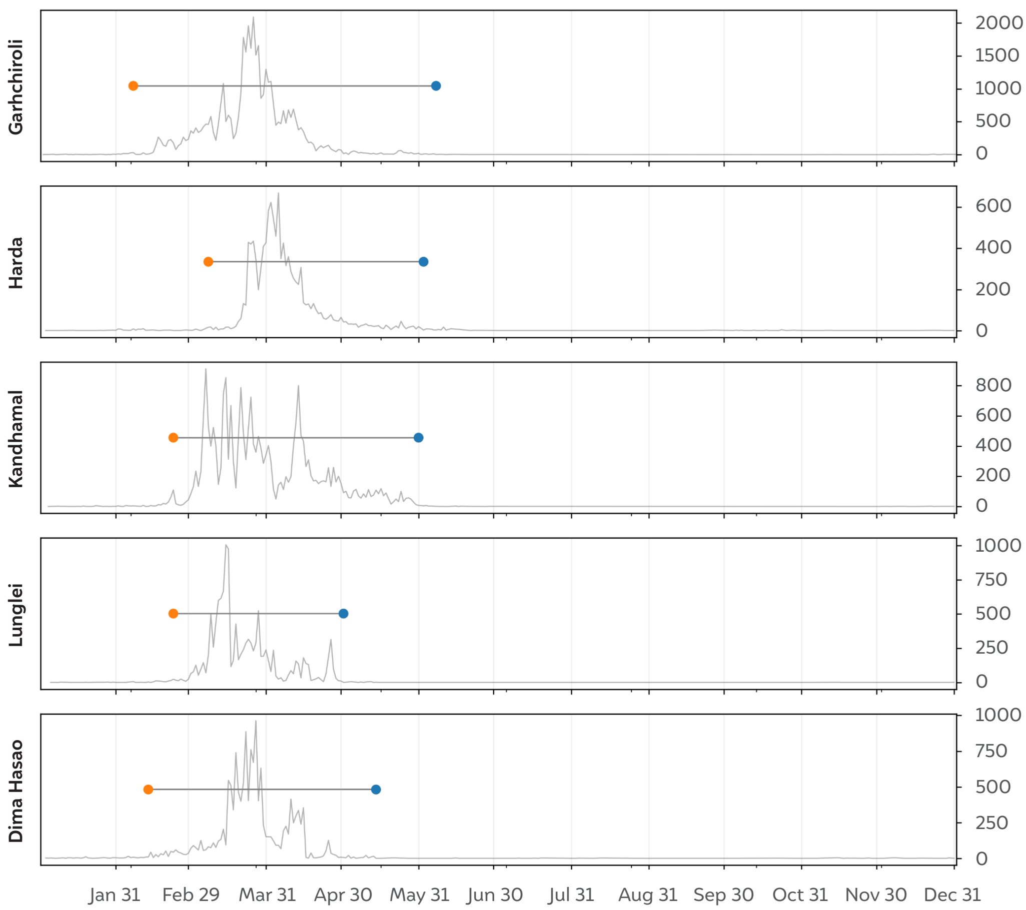
3.4 Impact of forest fires on local air pollution

Forest fires are major emitters of air pollutants, and as such, they have a significant impact on local air quality. With changing climatic and meteorological conditions, as the frequency and intensity of forest fires change, this trend is also likely to be reflected in air quality.

Large parts of India experience forest fires during the spring season (February–May), with the peaks across most states occurring between March and April on account of rising temperatures with the onset of summer (Pyush et al. 2018). Figure 7 shows the mean daily fire counts for the five leading district hotspots identified in Table 3 – Lunglei in Mizoram, Kandhamal in Odisha, Garhchiroli in Maharashtra, Harda in Madhya Pradesh, and Dima Hasao in Assam. The counts are averaged over the period between 2016 to 2021, highlighting the existence of a distinct 'fire season' between February and May.

Though several forest fires occur across the country throughout the year, few districts have the infrastructure needed to monitor the air quality impacts of these fires. None of the five leading hotspot districts has a single continuous ambient air quality monitoring station (CAAQM), so there is no reliable on-ground source of air

Figure 7 Spring sees a sharp increase in forest fire events in the leading hotspot districts

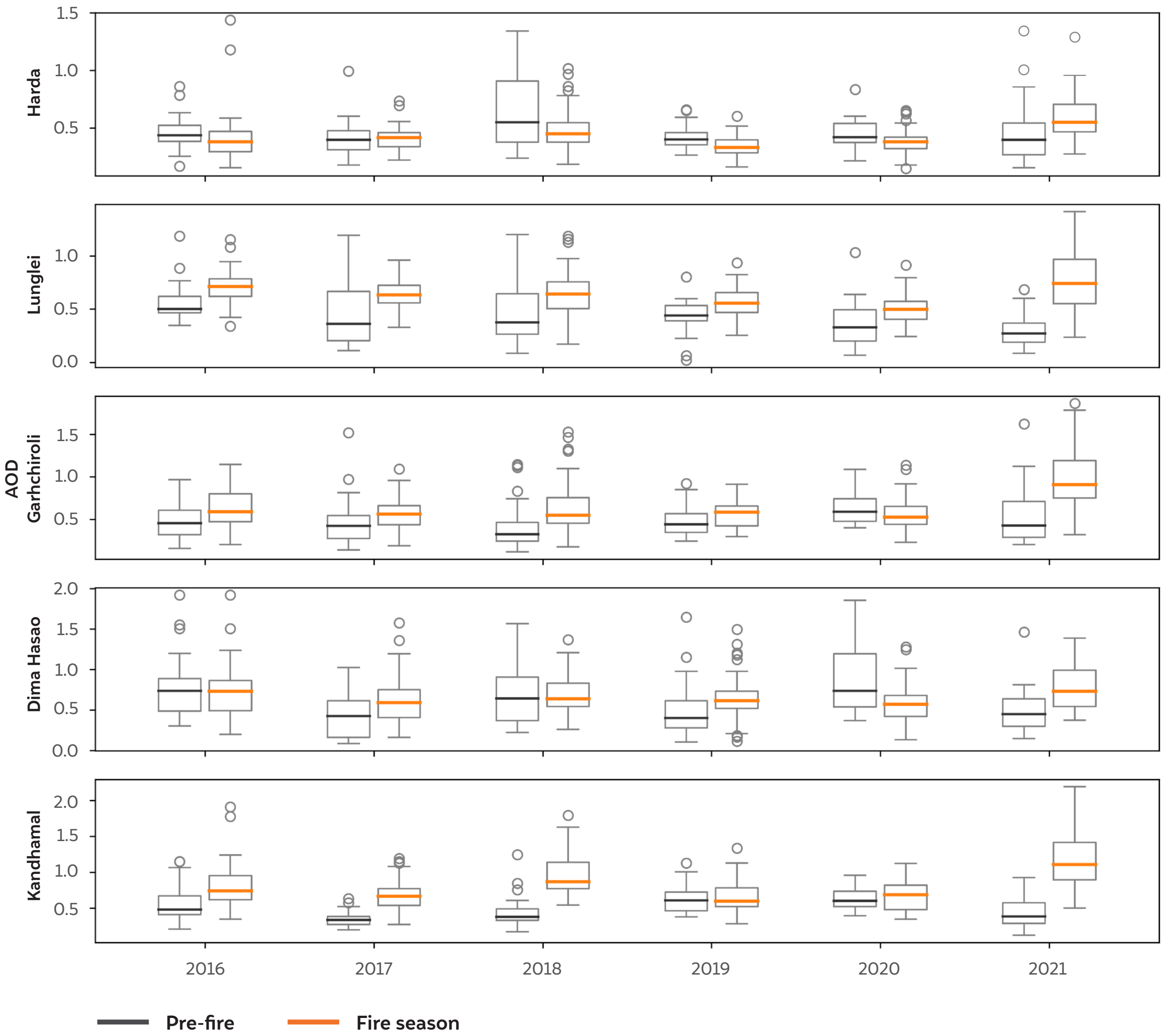


Source: Authors' analysis (orange and blue markers represent start and end of fire season, respectively) quality data. To account for this data gap and estimate the air quality impacts of forest fires in these districts, we look at the levels of AOD during the fire season and compare them with those in the period just before the first fires.[17]

Since the exact span of the fire season varies from district to district and even year to year in the same district due to differences in local conditions and meteorological parameters, we determined the fire season separately for each district and year by looking at when the fires started and subsided. The pre-fire period is defined as the 14 days immediately before the start of the identified fire season. Figure 8 highlights the trends in AOD levels across the five districts in the pre-fire period and the fire season over the past six years.

On average, across the leading hotspot districts, AOD was roughly 30 per cent higher in the fire season as compared to the pre-fire period. This increase also translates to greater concentrations of ground-level PM2.5 (Dey et al. 2020), which is one of the leading causes of premature mortality and severe respiratory disease in India and globally (Burnett et al. 2014).

Figure 8 Changes in AOD levels during the fire season and the pre-fire period in the leading hotspot districts



Source: Authors' analysis

17. Aerosol optical depth (AOD) is a satellite-derived measure of haziness and is widely used as a proxy for particulate levels in the atmosphere.

From Figure 8, we note that except for Harda in Madhya Pradesh, the fire season sees higher AOD values than the pre-fire period in all five hotspot districts. The anomaly in Harda could be due to various factors, including the fact that the district is close to Indore and Bhopal – two large cities, and due to mining areas in the southern part of Madhya Pradesh – which are potentially significant sources of emissions that could contribute to AOD. We also find that the average intensity of fires (as determined by the mean radiative power detected by the VIIRS satellite)[18] in Harda is the lowest of the five considered districts. In the period between 2016 and 2021, the mean radiative power of fires in Harda district was less than one-fifth of the mean across the remaining four districts in the same period. Low-intensity fires could represent prescribed fires by local forest authorities to manage forest fire risk (Noronha 2021), and they typically emit fewer pollutants.

We also note that the observed trend is weakest in 2020, with only three of the five districts showing higher AOD values in the fire season as compared to the pre-fire period in this year. This is likely because 2020 saw relatively fewer forest fires across these five districts (10,216 fires) compared to the annual average between 2015 and 2021 (17,025 fires). The lower number of fires in 2020 can be attributed to the delayed and above-average monsoon season in 2019 (Patel 2019), which reduced the availability of dry vegetation needed for forest fires. Further, reduced human activity in 2020 due to the Covid-19 pandemic could also have contributed to the low number of fires (Supriya 2020).

Our investigation into the impacts of forest fires on local air quality is based primarily on a satellite-based proxy for particulate matter concentrations, AOD. While this is useful in providing an understanding of the rise in pollution levels due to forest fires over large areas, it also has limitations. The primary limitation is the absence of continuous temporal data, since the earth-observing satellites used are non-geostationary. Also, since satellite-derived AOD is a columnar product, it cannot completely replace the high-quality data captured by ground-based sensors. It is important to complement satellite-based observations with ground-based air quality monitoring networks to develop a more robust understanding of the health effects and exposure levels of smoke-laden air due to forest fires. This reinforces the need for expanding air quality monitoring beyond urban areas to forested and fire-prone areas.

Image: iStock

18. Radiative power is a measure of the rate of radiant heat output from fires detected by VIIRS.

BOX 1 Additional key insights on the state of forest fires in recent years

This section enumerates key insights on the state of forest fires in recent decades from the ISFR 2021. While our analysis suggests that Andhra Pradesh, Assam, Chhattisgarh, Odisha, Maharashtra, Madhya Pradesh, Manipur, Mizoram, Nagaland, and Uttarakhand were extreme forest fire-prone states across the last two decades which is also confirmed in the India State of Forest Report (ISFR)[19] (ISFR 2021). However, the forest cover has increased by 1.6 per cent in the last five years (2015–2021) there has been an exponential spurt in forest fire incidences. Table 4 enumerates the hotspot states for 2019–2020. Similarly, Table 5 suggests that Garhchiroli, Kandhamal, and Bijapur were the most impacted districts in 2019–2020.

Table 4 **Odisha, Madhya Pradesh, Chhattisgarh were the most impacted by forest fire incidents in 2019–2020**

S.No.	2010–2019 (CEEW analysis)	2019–2020 (ISFR 2021)
1	Andhra Pradesh	Odisha
2	Assam	Madhya Pradesh
3	Chhattisgarh	Chhattisgarh
4	Odisha	Maharashtra
5	Maharashtra	Jharkhand
6	Madhya Pradesh	Uttarakhand
7	Manipur	Andhra Pradesh
8	Mizoram	Telangana
9	Nagaland	Mizoram
10	Uttarakhand	Assam

Source: Authors' compilation

Table 5 **Gadchiroli, Kandhamal and Bijapur were the most impacted districts in 2019–2020**

S.No.	2010–2019 (CEEW analysis)	2019–2020 (ISFR 2021)
1	Dima Hasao	Garhchiroli
2	Lunglei	Kandhamal
3	Lawngtlai	Bijapur
4	Mamit	Karbi Anglong
5	Harda	Kadapa
6	Jabalpur	West Singhbhum
7	Hoshangabad	Pauri Garhwal
8	Gadchiroli	East Nimar
9	Narayanpur	Mayurbhanj
10	Udham Singh Nagar	Sundargarh

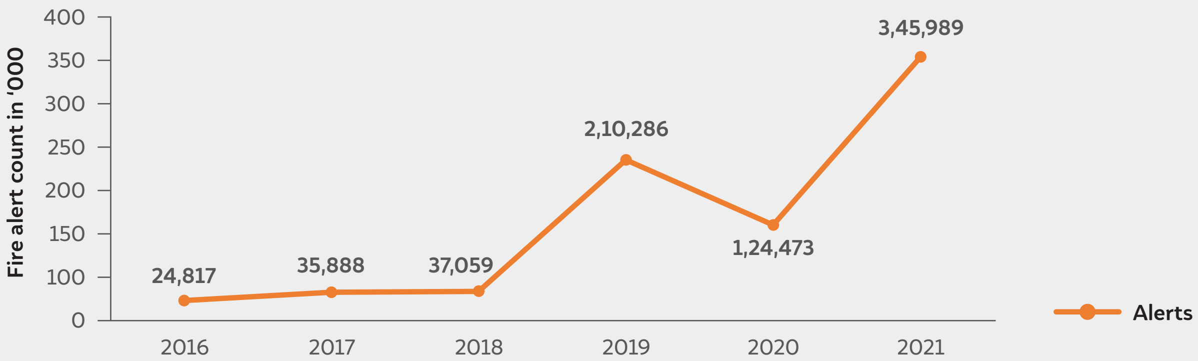
Source: Authors' compilation

There has been a significant improvement in forest fire management systems in recent decades; in the last six years alone, there has been a 14-times increase in forest fire alerts which is also inferred in our analysis as well in our decadal analysis (Figure 9) (ISFR 2015; 2021).

19. India State of Forest Report (ISFR) is a biennial publication of Forest survey of India (FSI), an organization under the Ministry of Environment Forest, & Climate Change, Government of India, engaged in the assessment of the country's forest resources and also provides analysis on forest fire incidences.

BOX 1 **Additional key insights on the state of forest fires in recent years**

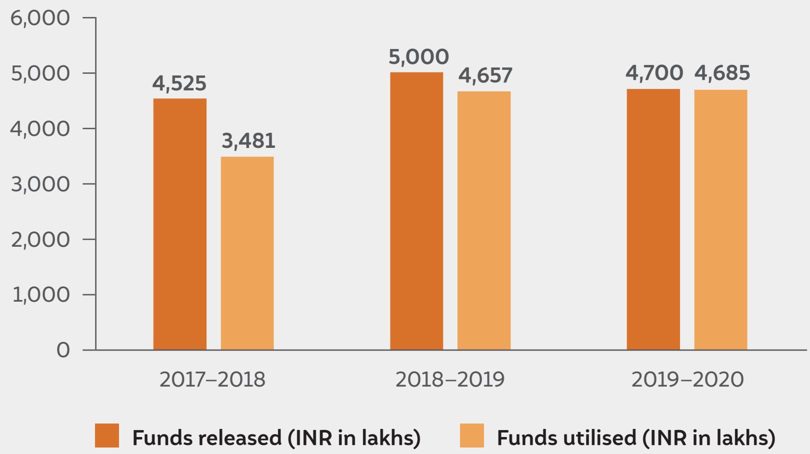
Figure 9 Forest fire alerts have tripled in number in 2020–2021



Source: ISFR 2021

Further, it is to be noted that the 14 per cent surge in forest fire alerts indicates the need for a more robust management system. The financial resource allocation toward forest fire management increased by a mere 3.4 per cent between 2017 and 2020 under the Forest Fires Prevention and Management Scheme in India (Figure 10). Managing forest fires effectively calls for an integrated and cohesive approach to save lives, livelihoods and ecosystem services.

Figure 10 Funds released and utilised under the Forest Fires Prevention and Management Scheme in India



Source: Authors' analysis based on Lok Sabha Unstarred Question No. 2189, Dated on 23.09.2020/ Union Budget 2021.

4. Conclusion

India is the second most vulnerable country to forest fires in the global south (Reddy. et.al 2019) and is experiencing an increasing trend of forest fires. Our analysis suggests that more than 62 per cent of Indian states are vulnerable to high-intensity forest fire events. Our study also generates evidence of how the varying and warming climate is intensifying forest fire incidences since most of the forest fire–prone districts are witnessing drought and drought-like conditions with increased dry spells.

India is aggressively marching ahead to achieve its NDCs and enhance its carbon sink; the likelihood of it achieving its Bonn challenge commitment of restoring 26 million hectares of degraded forests looks blurry, especially considering the soaring ten-fold increase in forest fire incidences over the last two decades. Adhering and applying principles of risk assessment for the effective management of forest fires can help climate-proof forests (CEEW 2015). The key recommendations from our study focus on the following four aspects:

4.1 Recognise forest fires as a disaster type and integrate them into national, sub-national and local disaster management plans

The *National Plan on Forest Fires* was launched by the Government of India in 2018 under the flagship *National Afforestation Programme*. This national plan touches upon a wide range of activities, but financial and operational dynamism remains a challenge. To provide further policy support, forest fires should be recognised as a disaster type under the *Disaster Management Act, 2005*. The recognition will enhance and strengthen the *National Plan on Forest Fires* by improving its financial allocation and creating a cadre of trained forest firefighters under the National Disaster Response Force (NDRF) and State Disaster Response Force (SDRF). The SFD officials are the first responders to any forest fire event; hence, state-focused localised forest action plans need to be developed, providing a decentralised operational and financial cushion for mitigating forest fire events. Further, forest fires as a hazard should be integrated and recognised in the NAPCC and State Action Plans on Climate Change (SAPCCs) that can have both mitigation and adaptation co-benefits. The integration will also help in the effective monitoring and financing of India's Bonn challenge commitments and NDCs. Managing forest fires needs a more robust systematic financial allocation and should go beyond one particular scheme.

4.2 Develop a forest fire-only alert system

Over the years, the forest fire management system in India has improved. Currently, FSI and NRSC use MODIS and Suomi NPP VIIRS information for near real-time monitoring of forest fires. The system does not segregate forest fires, waste burning, and crop burning; hence, ground validation takes time and often leads to misinformation. As a first step, a forest fire-only alert system needs to be developed that can provide real-time impact-based alerts. **There is a need to democratise forest fire data for better projection and incidence reporting and for the creation of an improved response and preparedness system**. A forest fire–based alert mechanism is the need of the hour and should be layered with localised weather and climatological variables that can predict ignition events. It should also be able to assess the extent to which the fire can spread and estimate the exposed populations based on wind speed, terrain, number of dry patches, etc. Although the FSI already puts out a Fire Weather Index, impact-based alerts will be crucial in mitigating forest fires. The alert system should serve the entire range of mitigation plans and enhance preparedness.

4.3 Enhance adaptive capacity

Enhanced adaptive capacity is required to climate-proof forests and forest-dependent populations. The approach for enhancing adaptive capacity should include i) identification of risks (forest fires, their impact on the ecosystem, lives, livelihoods, and the atmosphere), ii) understanding the extent of damage, iii) who could be/are the first set of responders (communities, forest dwellers and/or forest officers)? Based on this approach, communities and forest officials should be imparted tailor-made training to tackle forest fire events. Training on high technology–focused equipment such as drones and nature-based modules such as creating effective forest fire lines should be integrated.

4.4 Provide clean air shelters

Forest fires contribute significantly to the local air pollution; hence, real-time air quality monitoring is useful in assessing prevailing air quality conditions and exposure concentrations. Several examples from other countries demonstrate the application of smart monitoring using low-cost sensors and satellite data to track the impact of forest fires in a real -time fashion (Gupta et al. 2018). Moving forward, state pollution control boards should capitalise on the use of non-traditional monitoring networks such as low-cost sensors that are cost-effective and to plug in the data gaps. The state government/SFDs should repurpose public buildings like government schools and community halls by fitting them with clean air solutions like air filters to create clean air shelters for communities impacted by fires and smoke from forest fires. The SFD should work with pollution control boards and district administrations to assess air quality conditions during fire incidents and reach out to the affected communities to ensure that they are taking protective measures to reduce their exposure to the smoke-laden air.

> **More than 275 million people in India are exposed to extreme forest fire events.**

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The authors

Abinash Mohanty
abinash.mohanty@ceew.in | @Abinash0294

Abinash is a Programme Lead with the Risks and Adaptation research focus area at CEEW. His work primarily involves designing decision-making toolkits for effective policymaking around the intricacies of climate change risks, sustainability, and environmental resources management. He is also a reviewer of the IPCC's sixth assessment report on *Impacts, Adaptation and Vulnerability* (AR6).

Vidur Mithal
vidurmithal@gmail.com | @vidurmithal

Vidur was a research intern with the Risks and Adaptation research focus area at CEEW. As a research intern at CEEW, he primarily worked on air quality, focusing on its monitoring and modelling, and on the development of data-based tools to map and analyse climate risks.

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COUNCIL ON ENERGY, ENVIRONMENT AND WATER (CEEW)

Sanskrit Bhawan, A-10, Qutab Institutional Area
Aruna Asaf Ali Marg, New Delhi - 110067, India
T: +91 (0) 11 4073 3300

info@ceew.in | ceew.in | @CEEWIndia | ceewindia