Framework for eForest fire management in the shifting cultivation-dominated landscape of Meghalaya, North East India, using remote sensing and GIS

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Meghalaya, 'the abode of clouds' is one of the states of North East India. The state witnesses several forest fire incidents every year. In this study, MODIS-based forest fire counts from 2003 to 2023 have been used for the generation of forest fire-prone and vulnerability maps. The forest fire vulnerability map has been generated at 1 : 10 k for the entire state and at 1 : 5 k for Reserve Forests, Community Reserve Forests and other Protected Areas. Ri Bhoi and West Khasi Hills districts witness high forest fire incidents compared to all the other districts. Maximum number of forest fire occurs in moderately dense and very dense forests. The eForest Fire Information System, viz. 'Meghalaya Forest Fire Information System' has a dashboard with geospatial forest fire information and a forest fire incident reporting android based app developed for fire managers both at Government and community level. Shifting cultivation (jhum) is a predominant land-use pattern; therefore the framework has embedded jhum area information for improving forest fire management strategies to match the local scenario.

Keywords: Forest fire, mitigation measures, remote sensing, shifting cultivation, vulnerability maps.

OCCURRENCE of a forest fire in the forest ecosystem is linked to natural recycling of nutrients, regeneration of species, removal of weeds, maintaining habitat quality and shaping a forest community[1–4], it acts like an environmental filter and governs ecological succession[5,6]. In recent times, forest fires are increasing mainly caused by human activities[7,8]. Due to their extent of damage, forest fires are regarded as major degenerating factors, damaging the growing stock and making the area vulnerable to erosion[6].

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According to Tyukavina *et al.*[9], 26–29% of the global 2001–2019 forest loss was due to fire, which is higher than previous estimates of 21–25% for 2001–2015 (ref. 10) and 12–18% for 2003–2014 (ref. 11). At least half of the global forest losses caused by natural and anthropogenic drivers is associated with fire[10].

The forests of North East (NE) and central India have more fire-prone areas in the country (Forest Survey of India (FSI), 2019). Forest fire studies in Meghalaya have raised concerns over their frequent occurrence due to shifting cultivation and other human activities, and the need for scientific forest fire management strategies[12–14].

Increased incidences of forest fire have prompted Government intervention and schemes aimed at preventing and controlling them[15]. Meghalaya in NE India, has constituted State Crisis Management Groups (SCGs) and a Crisis Management Cell to involve the local communities in forest fire protection by setting-up a Village Forest Fire Control Committee. The Joint Forest Management Committees also help combat forest fires, especially in the plantation areas. Forest fire control is an essential part of forest management[16].

This study aims to present an eForest Fire Information System using remote sensing and GIS-based information in a single window platform, namely 'Meghalaya Forest Fire Information System' (MeFFIS). This platform consists of a forest fire dashboard that integrates geospatial analytics and ground-based information collection through mobile application. The purpose of MeFFIS is to involve Government decision-makers and local communities in effective fire suppression and management. Shifting cultivation (jhum) is a predominant land-use category and a major cause of forest fires in Meghalaya. Therefore the forest fire assessment has been carried out in jhum and non-jhum areas for planning effective fire management strategies by forest fire managers in the jhum- and the non-jhum-prone areas.

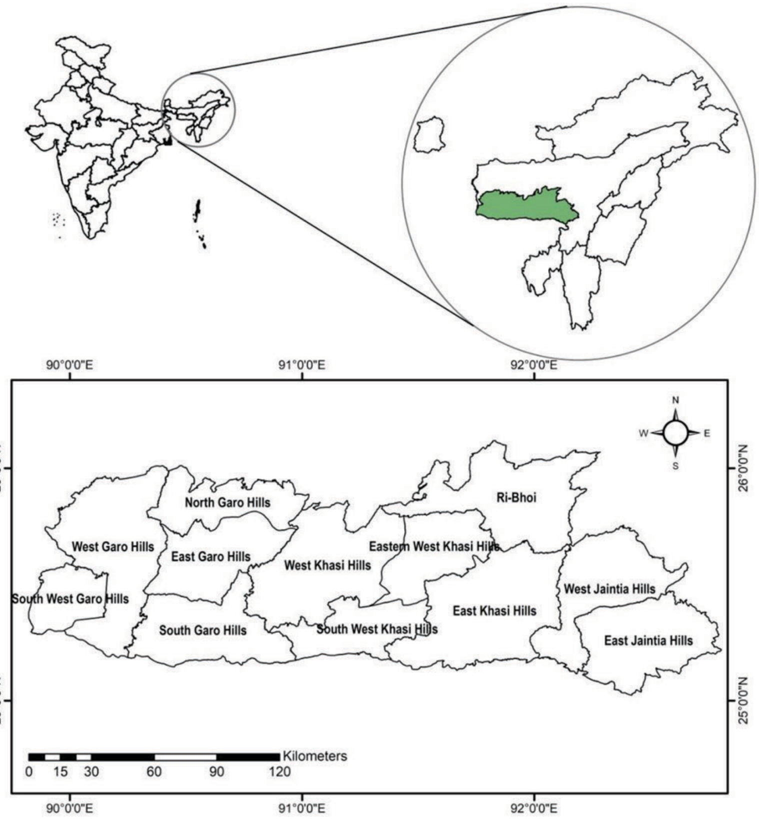

Figure 1. Study area.

Study area

Meghalaya is situated between 25.1–26.7°N lat. and 89.50–92.48°E long. The state is bordered by Assam in the north and east, and shares an international boundary with Bangladesh in the south and west. The geographical area of Meghalaya is 22,429 km^2. This study has been carried out for the entire state (Figure 1), including districts blocks, Government-Owned Forests (GOFs) consisting of Reserve Forests (RFs) and Protected Forests (PFs) as well as Protected Areas (PAs) that include Community Reserves (CRs), Wildlife Sanctuaries (WLS) and National Parks (NPs), Biosphere Reserves (BRs) and Eco-Sensitive Zones (ESZs).

According to India State of Forest Report[17], forest cover in Meghalaya is 17,046 km^2, which is 76% of the state's geographical area. The dominant forest types according to the Champion and Seth[18] classification are East Himalayan moist mixed deciduous forests, Khasi sub-tropical wet hill forest, Cachar tropical evergreen forest, Assam sub-tropical pine forest and Khasi hill sal.

Data used and methodology

The present study incorporates a diverse theme of spatial layers essential for a comprehensive analysis and understanding of forest fires. Forest fire data from 2003 to 2023 based on Moderate Resolution Imaging Spectroradiometer (MODIS)[19,20] and forest-type map for fuel characteristics were obtained from Forest Survey of India (https://fsi-forestfire.gov.in). Forest cover and land-use classes for the year 2022 were prepared using IRS LISS IV (5.8 m resolution) and Cartosat-2 series (2.5 m resolution) satellite imagery procured from the National Data Centre, National Remote Sensing Centre, Hyderabad, Indian Space Research Organization (ISRO). The Carto DEM data with 10 m resolution were used to generate topographic information on elevation, slope and aspect. The notified forest boundaries were obtained from Forest and Environment Department, Government of Meghalaya. Information on jhum areas was obtained from land-use/land-cover (LULC) maps of 2005–06, 2011–2012, 2015–2016, 2017–2018 and 2021 (available from the North Eastern Space Applications Centre data repository).

Geospatial assessment of forest fire-prone areas

The forest fire-prone map was generated by computing frequency of fire occurrence (historical forest fire incidents) within a uniform grid of 1 km × 1 km, which was then classified into different fire-prone categories. The average annual frequency was calculated by dividing the total frequency by the number of years and fire-prone areas were categorized into severity classes based on the average frequency of forest fire in each grid per year[21]. The fire-prone categories include:

(i) Very high – average frequency ≥0.48.
(ii) High – average frequency ≥0.24 and <0.48.
(iii) Moderate – average frequency ≥0.12 and <0.24.
(iv) Low – average frequency ≥0.06 and <0.12.
(v) Very low – average frequency <0.06.

Geospatial analysis of forest fire vulnerability

Vulnerability assessment is a prerequisite to plan forest adaptation[22,23] in order to deal with the risk to forests under climate change[24]. The forest fire vulnerability map was generated based on factors like forest type, forest density, elevation, slope, aspect, distance to road and distance to settlement. The vulnerability analysis was carried out using analytic hierarchy process (AHP), a decision-making method notable for its systematic and quantitative prioritization of factors. A precedence weighting was derived and combined to determine the global ranking score of each relevant criterion[25]. A two-step AHP was employed to generate the vulnerability map, i.e. (i) assessment of weightage within the categories/parameters, and (ii) comparison of weightage between the categories/parameters. To compute the weights for different criteria, AHP builds a pairwise comparison matrix. Each value (a_{jk}) of the matrix represents the importance of the jth layer relative to the kth layer. If two layers have the same importance, then the value of a_{jk} is 1. The values a_{jk} and a_{kj} fulfil the constraint as given in eq. (1).

$$a_{jk} \cdot a_{kj} = 1. \tag{1}$$

The relative importance between two layers is measured on a numerical scale from 1 to 9, which forms a matrix. After the matrix was prepared, the normalized pairwise comparison matrix was computed by making the sum of the values equal to 1 on each column. Normalized matrix can be computed as presented in eq. (2).

$$'a_{jk} = \frac{a_{jk}}{\sum_{l=1}^{m} a_{jk}}. \tag{2}$$

Finally, the criteria weight vector W (that is, an m-dimensional column vector) was built by averaging the entries on each row (eq. (3)) as

$$W_j = \frac{\sum_{i=1}^{m} {'a_{jk}}}{m}. \tag{3}$$

Using the weightage of different variables for forest fire, vulnerability was determined as

Vulnerability = Forest type × 0.29 + forest density × 0.21 + settlement × 0.19 + slope × 0.15 + road × 0.06 + aspect × 0.05 + elevation × 0.05.

To check the consistency of decision-making and reduce the bias in the process, a consistency ratio (CR) was obtained as

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}}, \tag{4}$$

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n-1}, \tag{5}$$

where CI is the consistency index. The consistency ratio (CR) is a metric that indicates the consistency between pairwise comparisons. Saaty[26] has shown that a CR of 0.10 or less is acceptable to continue the AHP analysis. RI is the consistency index of a randomly generated comparison matrix and is available to the public in tables. $\lambda_{\max}$ is the largest or principal eigen value of the matrix that can be easily calculated from the matrix[27].

The forest fire vulnerability map was generated for the entire state of Meghalaya at 1 : 10 k scale and for all the RFs, PFs, NPs, ESZs and CRs; the vulnerability map was generated at 1 : 5 k scale. Evaluation of classification accuracy of all the LULC thematic maps was based on the use of error matrix or contingency table. The accuracy of each of the LULC maps was assessed to be between 90% and 92%. However, the remaining datasets were taken from different sources which are available for download following necessary quality checks. The maps were also verified using forest fire incident data and field verification.

Development of mobile app and Meghalaya Forest Fire Information System

An integrated localized eForest fire management framework has been envisaged for Meghalaya with the development of a ground-based mobile application and a monitoring dashboard for forest-fire managers. The dashboard contains geospatial information on Meghalaya forest fires and the ground-based information collected through the mobile app by the field staff or local persons.

The app has a provision to report the forest fire incidents and traverse burnt areas to ascertain the causes and for area estimation of the burned sites, with a facility to upload data in English and the local languages spoken in Meghalaya. This information is then uploaded on the server along with coordinates which can be accessed by Forest Department officials. The forest fire app also has the facility to upload

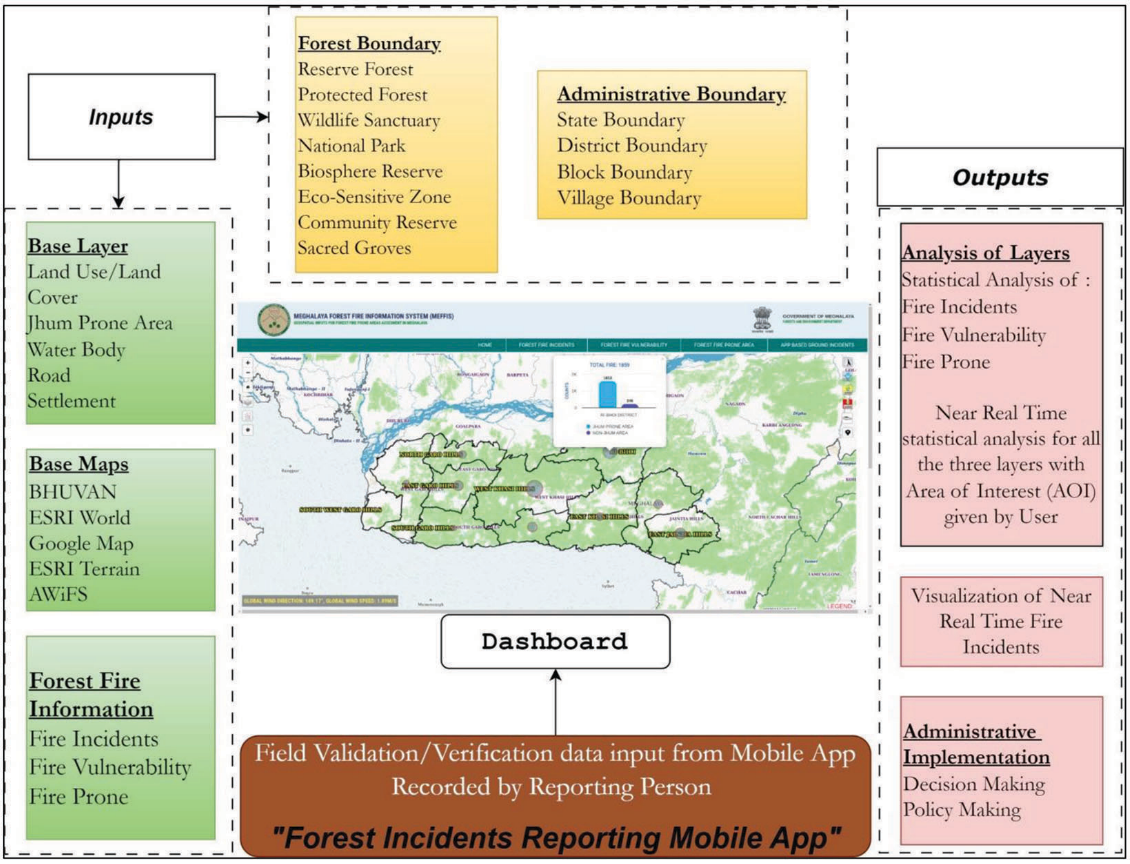

Figure 2. Integrated forest fire framework.

Table 1. District-wise forest fire incidences in Meghalaya, based on MODIS data (2003–2023)

	District												
Year	East Garo Hills	East Jaintia Hills	East Khasi Hills	Eastern West Khasi Hills	North Garo Hills	Ri Bhoi	South Garo Hills	South West Garo Hills	South West Khasi Hills	West Garo Hills	West Jaintia Hills	West Khasi Hills	Total
2003	154	148	131	106	82	328	175	37	142	280	75	201	1,859
2004	228	170	114	153	198	537	198	33	126	253	88	336	2,434
2005	261	157	76	80	170	358	202	31	111	190	49	185	1,870
2006	359	259	220	194	199	646	270	45	142	295	110	412	3,151
2007	243	222	83	79	187	381	275	58	148	339	61	315	2,391
2008	131	142	66	73	116	409	155	30	90	200	41	237	1,690
2009	331	251	260	118	244	597	206	26	190	263	125	470	3,081
2010	468	172	183	124	326	479	118	7	124	241	111	489	2,842
2011	331	186	104	87	107	342	162	25	85	229	119	224	2,001
2012	265	182	235	214	173	471	163	12	190	156	125	443	2,629
2013	256	194	95	87	134	490	113	17	121	120	99	296	2,022
2014	280	217	154	130	163	520	169	10	148	193	113	301	2,398
2015	296	258	130	74	167	537	202	12	157	221	96	368	2,518
2016	181	205	54	121	161	546	124	11	109	141	82	306	2,041
2017	258	115	54	111	124	452	143	5	75	219	110	257	1,923
2018	264	188	101	98	146	462	161	13	122	134	104	367	2,160
2019	170	113	52	45	91	346	110	5	78	114	66	186	1,376
2020	193	177	86	103	154	409	95	7	137	112	54	326	1,853
2021	138	274	106	110	110	469	95	5	164	116	98	393	2,078
2022	219	199	67	50	94	301	76	0	63	132	53	287	1,541
2023	141	188	87	67	80	278	73	4	125	64	91	301	1,499
Total	5,167	4,017	2,458	2,224	3,226	9,358	3,285	393	2,647	4,012	1,870	6,700	45,357

field points in offline mode, which gets uploaded whenever internet connection is available.

The forest fire dashboard has been developed considering the easy access of data on forest fires at the local level.

Table 2. Fire count in different input parameters

Parameters	Class	Fire count (%)
Forest type	East Himalayan moist mixed deciduous forest	58.43
	Khasi subtropical wet hill forest	16.24
	Assam subtropical pine forest	7.35
	Sal forest	5.25
	Cachar tropical evergreen forest	4.46
	Pioneer Euphorbiaceous scrub	3.50
	Secondary moist bamboo brakes	3.27
	TOF/plantation	1.09
	Semi-evergreen forest	0.42
Forest density (cover)	Moderate	47.83
	Dense	20.56
	Open	15.39
	Scrub open	10.68
	Scrub dense	5.54
Distance from settlement (m)	1000	31.04
	1500	21.89
	500	20.94
	2000	12.63
	2500	6.69
	3000	3.34
	3500	1.74
	>3500	1.71
Slope(°)	20	39.07
	30	26.74
	10	16.89
	40	8.62
	<5	7.05
	>40	1.64
Distance from road (m)	200	29.78
	400	20.68
	600	15.15
	800	10.66
	1000	7.56
	1200	4.98
	1400	3.47
	1600	2.27
	1800	1.62
	2500	1.32
	2000	1.02
	3000	0.69
	3500	0.43
	>3500	0.38
Aspect	NW	14.51
	SE	13.75
	W	12.98
	E	12.32
	S	12.30
	SW	11.79
	N	11.44
	NE	10.91
Elevation (m)	200–400	22.60
	400–600	18.37
	600–800	16.60
	1000–1500	14.05
	800–1000	13.78
	0–200	11.24
	>1500	3.35

The dashboard contains information on near real time and historical forest fire incidents (from FSI), fire-prone zones and forest fire vulnerable zones. This information can be visualized for the entire state, districts, blocks, RFs, PFs, CRs, ESZs and NPs for management. There is a facility for the users to generate area estimates under each category by selecting the boundaries already embedded in the dashboard, or by demarcating their own areas of interest, or by uploading the external shapefiles. The forest fires are classified into jhum-prone and non-jhum-prone based on the shifting cultivation map. There are several other important maps like road, settlements, etc. integrated into the system. Figure 2 shows the integrated forest fire framework.

Results and discussion

A total of 45,357 counts of fire incidence (MODIS) from 2003 to 2023 were observed in Meghalaya. Maximum fire incidences occurred in the year 2006 (3151), followed by 2009 (3081). The minimum forest fire incidence was reported in the year 2019 (1376).

Among the districts of Meghalaya, Ri Bhoi and West Khasi Hills had the highest forest fire incidences from 2003 to 2023. South West Garo Hills district had the lowest fire incidence throughout the study period. Table 1 gives the overall forest fire information in the state and district-wise forest fire counts for different years.

Table 2 shows the parameters used to derive forest fire vulnerability, viz. forest type, forest density, proximity to road and settlement, slope, aspect, elevation and distribution of the fire incidents observed in each parameter. Out of the total forest cover in the state, 41.95% area is under high and very high vulnerability category. Table 3 and Figure 3 present the area and spatial extent of forest fire vulnerability. Table 4 gives the district-wise scenario of forests vulnerable to fire.

Forest fire-prone map has been categorized into five classes, viz. very low, low, moderate, high and very high. The result shows the spatial distribution of the zones based on frequency of fire counts. Meghalaya has 45.30% under very low category, followed by 22.35% under moderate category. Table 5 gives the forest fire proneness under different categories. Figure 4 presents the forest fire-prone map of Meghalaya. Table 6 gives the district-wise scenario of forests prone to fire. The forest fire incidents and field visits have been used for the validation of the spatial maps.

Table 3. Area under forest fire vulnerability classes in Meghalaya

Fire vulnerability class	Area (%)
Very low	22.83
Low	13.21
Moderate	21.98
High	24.42
Very high	17.53

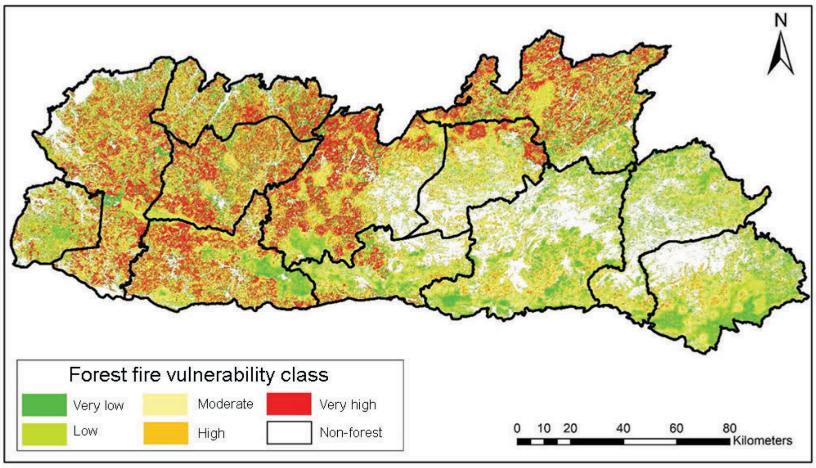

Figure 3. Forest fire vulnerability map of Meghalaya, North East India.

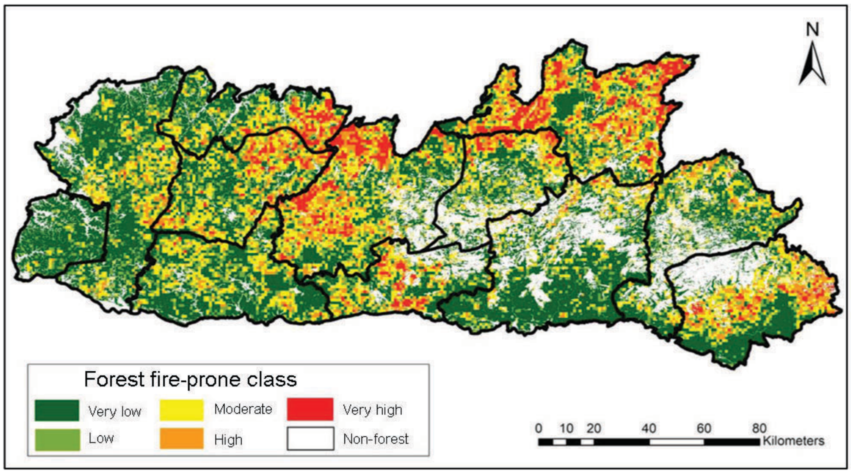

Figure 4. Forest fire-prone map of Meghalaya.

Table 4. Area (%) under forest fire vulnerability classes in various districts of Meghalaya

District	Very low	Low	Moderate	High	Very high
East Garo Hills	19.21	5.39	16.26	30.68	28.46
East Jaintia Hills	31.33	31.01	26.14	10.86	0.66
East Khasi Hills	29.10	23.30	31.75	15.06	0.79
Eastern West Khasi Hills	19.09	9.34	29.56	29.83	12.18
North Garo Hills	25.60	5.59	14.06	29.44	25.32
Ri Bhoi	21.65	6.23	18.94	27.66	25.51
South Garo Hills	17.17	11.19	19.29	28.52	23.84
South West Garo Hills	30.12	10.03	15.97	30.86	13.03
South West Khasi Hills	22.40	23.84	28.72	17.31	7.74
West Garo Hills	19.99	6.27	16.75	30.19	26.79
West Jaintia Hills	30.88	24.79	32.20	11.15	0.98
West Khasi Hills	16.38	8.68	18.67	29.17	27.10

The forest fire record shows an increasing trend with manipulated fire regime due to anthropogenic activities leading to permanent changes to the ecosystem and its components[4,28]. The forest fire vulnerability map of Meghalaya was generated to identify the probable areas of fire occurrence and the fire-prone map depicts the areas of actual fire occurrence. This information will help the forest-fire managers to take appropriate steps for fire control. The

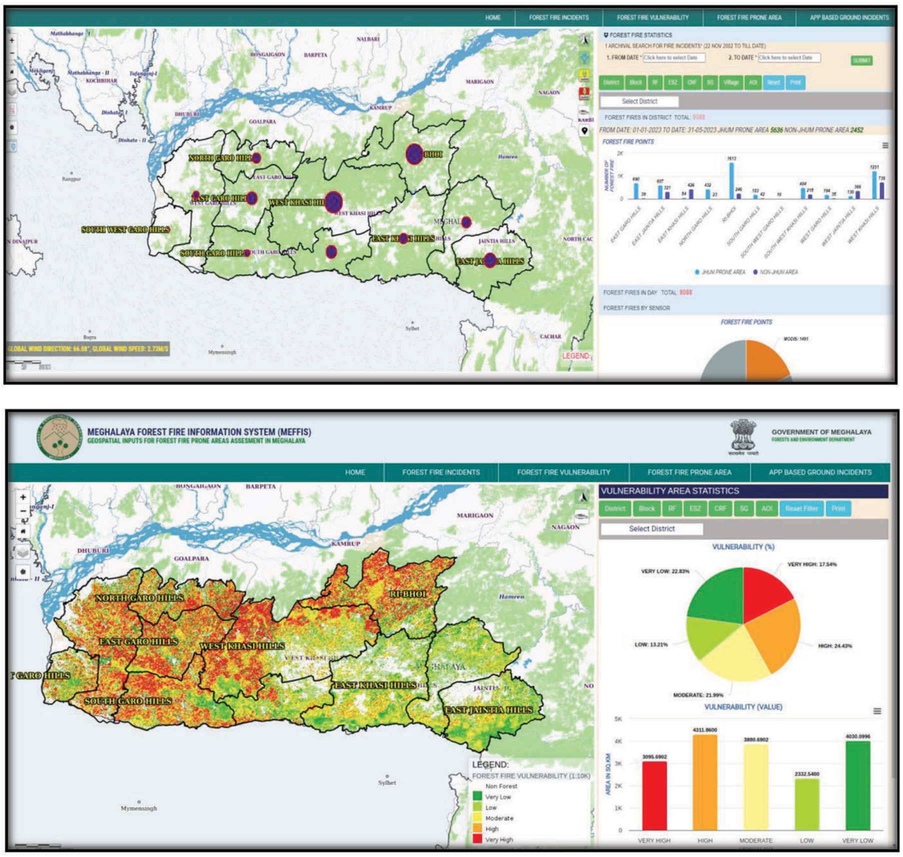

Figure 5. Snapshots of the MeFFIS dashboard.

Table 5. Area under forest fire-prone classes in Meghalaya

Fire-prone class	Area (%)
Very low	45.30
Low	13.45
Moderate	22.35
High	12.94
Very high	5.96

concentration of forest fires in narrow topographic zones and proximity zones of built-up areas in Meghalaya reflects the anthropogenic nature of forest fires in this region. It can be observed that some areas, like East Jaintia Hills district, though categorized it is under moderate vulnerability zone, are classified under high to very high forest fire-prone zones. Such variations are due to the anthropogenic nature of forest fires, particularly due to the prevalence of jhum. For efficient and effective forest fire management, an attempt has been made in this study to distinguish forest fires as jhum and non-jhum. Jhum fires are limited to jhum cultivation areas. Such forest fires can be controlled only by controlling jhum cultivation. Non-jhum fires in the State normally occur in coniferous pine forests and deciduous forests. Management of forest fires in non-jhum areas should ideally be directed to the management of their source, i.e. a thick contiguous layer of dry combustible litter. Management may include diversion, destruction and division of the litter. Diversion of the litter may involve its collection and use as fuel (briquette), fibre (rope weaving), fertilizer (composting) and furnishing (filling for mattresses, pine-cone handicraft). Destruction may involve increasing the rate of decay of the litter by improving moisture regime in the forest floor through the construction of check dams, contour trenches, interception trenches and other moisture-conservation structures; gradual replacement of conifer and deciduous species by evergreen species and periodic controlled burning of accumulated dry litter. Division includes fragmentation of the contiguous layer of the litter by construction and regular cleaning of conventional dry fire lines consisting of about 3 m wide strips completely devoid of any litter or vegetation and self-sustaining natural wet fire lines consisting of strips or shelterbelts of evergreen species at regular intervals.

The need for a real-time early warning system as a preventive measure has been emphasized[29]. The selection and development of appropriate fire management options should take into account local circumstances and conditions like forest type, risk and sources of fire, access and terrain, climatic conditions, adjoining land uses and socio-economic

Table 6. Area (%) under various forest fire-prone in districts of Meghalaya

District	Very low	Low	Moderate	High	Very high
East Garo Hills	34.48	13.79	28.20	17.00	6.53
East Jaintia Hills	39.96	10.90	23.10	20.04	6.00
East Khasi Hills	68.25	13.13	13.53	4.61	0.48
Eastern West Khasi Hills	39.02	14.80	26.98	13.26	5.95
North Garo Hills	41.48	11.63	23.54	13.19	10.15
Ri Bhoi	23.58	9.92	25.45	24.58	16.47
South Garo Hills	53.24	16.62	23.66	5.95	0.53
South West Garo Hills	84.80	10.25	4.63	0.32	0.00
South West Khasi Hills	39.43	13.90	24.29	15.65	6.72
West Garo Hills	59.07	15.32	19.24	5.95	0.43
West Jaintia Hills	53.51	16.87	21.86	7.25	0.52
West Khasi Hills	28.87	13.38	26.54	19.21	12.00

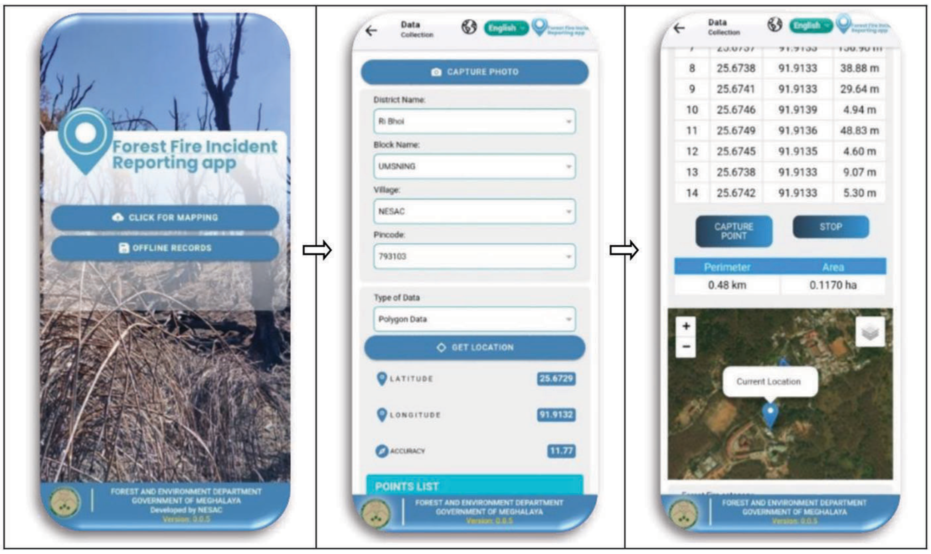

Figure 6. Snapshots of the mobile app.

factors[30]. The availability of local-level information has been achieved by improving the scale of mapping and spatial distribution of jhum cultivation areas. In this direction, for better forest fire management, MeFFIS will contain unique information on forest-fire occurrence based on satellite and ground-based monitoring along with the geospatial information on fire vulnerability, fire-prone areas in various administrative units as well as community forests and other forest areas of the entire State. Figure 5 provides a view of the dashboard.

The information collected through the mobile app downloadable from Google Play Store has the potential for use at the community level. Figure 6 shows the layout of the app. This app has the advantage of mapping the forest incidents that are missed out due to timing of the satellite pass and fire occurrence, as well as small-sized fire incidents that are missed due to limitation of satellite resolution.

According to FAO[31] the data produced by any remote sensing activities should be integrated into a Fire Management Information System so that, through the combination of data from various sources, more information can be extracted to better support management decision-making.

Conclusion

Forest fires covering almost the entire State of Meghalaya every year are mainly attributable to anthropogenic causes. The drivers of anthropogenic forest fires in Meghalaya, as observed from field visits, are shifting cultivation, broom grass cultivation, timber collection, NTFP collection, forest floor clearing (in pine forests) and charcoal burning. The majority of forests in Meghalaya are owned by communities, clans and private individuals; thus forest fires cannot be controlled without active involvement of the local communities. This study presents a comprehensive analysis of the forest fire scenario in Meghalaya and suggests mitigation measures for Government Departments and local communities through recent technological interventions. The information available in the fire dashboard can be effectively utilized by the Government Departments and the local communities. More ground-based information and participation can be achieved through the developed mobile app. The forest fire information available in the dashboard can also help generate awareness regarding the forest fire scenario in Meghalaya. This study also suggests framing of different forest fire prevention and mitigation strategies in the shifting cultivation-dominated areas. Thus, the entire system is a practical solution for effective mitigation of forest fires in Meghalaya.

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