




Research Article

Forest fire risk mapping using analytical hierarchy process (AHP) and earth observation datasets: a case study in the mountainous terrain of Northeast India

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Received: 9 December 2020 / Accepted: 16 February 2021 / Published online: 6 March 2021
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Abstract

This study presents a geospatial approach in conjunction with a multi-criteria decision-making (MCDM) tool for mapping forest fire risk zones in the district of Ri-Bhoi, Meghalaya, India which is very rich in biodiversity. Analytical hierarchy process (AHP)-based pair-wise comparison matrix was constructed to compare the selected parameters against each other based on their impact/influence (equal, moderate, strong, very strong, and extremely strong) on a forest fire. The final output delineated fire risk zones in the study area in four categories that include very high-risk, high-risk, moderate-risk, and low-risk zones. The delineated fire risk zones were found to be in close agreement with actual fire points obtained from Moderate Resolution Imaging Spectroradiometer (MODIS) fire data for the study area. Results indicated that Ri-Bhoi's 804.31 sq. km. (32.86%) the area was under 'very high' fire susceptibility. This was followed by 583.10 sq. km. (23.82%), 670.47 sq. km. (27.39%), and 390.12 sq. km. (15.93%) the area under high, moderate, and low fire risk categories, respectively. These results can be used effectively to plan fire control measures in advance and the methodology suggested in this study can be adopted in other areas too for delineating potential fire risk zones.

Keywords Forest fire · MCDM · AHP · Geospatial approach · Northeast India

1 Introduction

Natural conservation areas that play an important role in maintaining the environmental balance are found in developing tropical regions forests [1–3]. Despite being of paramount importance, forest cover loss in these regions is occurring at an alarming rate [4–6]. Over the last few decades, decline in forest cover has been attributed to wildfires, rapid economic development, agriculture, logging, and increasing human population [7–10]. Globally, approximately, 30% of tropical forests were degraded by logging or fire between 2000 and 2012 [11, 12].

In India, approximately, 64% of the total forest area is frequently affected by forest fires [13], causing an

economic loss of over 440 crores [14]. Forest fires can be caused naturally (e.g., lighting) and/or induced via human activities, however, in India the latter is dominant. About 90% of the forest fires in India are caused by humans [15]. Over the last few years, forest fires in India have received greater attention because of their ecological, economic, social, climatic, and political impacts [16]. Despite the fact that forest fires are mostly regulated by anthropogenic factors, local environment, metrological condition, and topography factors also play an important role in their uncontrolled expansion. In this regard, it is very important to identify vulnerable areas that come under "forest fire risk zones." Therefore, parameters that play an

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important role in forest fire need to be quantified timely with advanced technology.

Timely and accurate information of complex fire models needs spatial and temporal information that is furnished by geospatial technologies [17–21]. Additionally, integration of multi-criteria decision-making (MCDM) in spatial domain provides a novel framework toward the assessment of fire risk zones [2, 16, 22–28]. The AHP method is among the most widely used MCDM [29]. AHP along with geospatial techniques has been successfully utilized for identifying the fire risk zones in many parts of the world [3, 30–35].

The present study focuses on Ri-Bhoi district of Meghalaya state which lies in the northeastern (NE) region of India. In this region, slash and burn shifting cultivation, locally known as 'Jhum,' plays an important role in a forest fire [36–38]. Being a forest-dominated region, forest fire risk assessment in this area is the need of the hour [39]. Additionally, no such methodology/model prior to the present study has been explored for mapping fire risk zones in the study area. The present study expects to aid in devising and adopting appropriate strategies for avoiding/minimizing the damage caused by forest fires in the study area.

2 Study area

The Ri-Bhoi district of Meghalaya lies between 91°20'E and 92°20'E longitude and 25°20'N and 26°20'N latitude of the northeast region of India (Fig. 1). It covers an area of 2448 sq. km. and is bounded by Kamrup district of Assam in the North, Karbi Anglong district of Assam and Jaintia Hills in the East, East Khasi Hills district in the South and West Khasi Hills district in the West of the state. The major forest species of the study area were *Tectonagrandis* (Teak), *Shorea robusta* (Sal), *Bambusa vulgaris* (bamboo), *Thysanolaena* (broom grass), *Arundinaria* or cane. According to census 2011, 71% of the population in this region was engaged in agriculture where the traditional method of shifting cultivation was the dominant form of practice for agriculture. The important agricultural products of the region were *Oryza sativa* (Rice), *Zea mays* (Maize), Oilseeds, *Ananas comosus* (Pineapple), *Musa paradisiacal* (Banana), *Carica papaya* (Papaya), *Artocarpus heterophyllus* (Jackfruit), *Manihot esculenta* (Cassava), *Zingiber officinale* (Ginger) on which major portion of the population in the district depends for their livelihood. In summer, the climate of the district is hot and humid. Maximum temperature in the northern part of districts goes up to 31.06 °C during summer, whereas winter is mild with a temperature rising to 20.04 °C.

The area was inhabited by the Bhois, a Khasi sub-tribe. The district had an elevation of 25–1358 m above mean sea level where Sohpetbneng (1350 m) and the Raitong (1237 m) were the most important peaks of the district. The soil of the district was derived from Gneissic complex parent materials; they were dark reddish-brown where the texture of soil varied from loamy to fine loamy, whereas the areas bordering Assam were mostly covered with alluvial soil. The important rivers flowing through this region include the Umtrew, Umsiang, Umran, and Umiam. Ri-Bhoi district was a dwelling to numerous flora and fauna known as the Nongkhylllem Wildlife Sanctuary. The study area mostly belonged in a rural area where several agricultural products, fruits, oilseeds, etc., were sold in the various market of the district. Shifting cultivation was the dominant source of livelihood in this region as a substantial portion of the population depended on it for their economic profits. For the farmers, shifting cultivation became more of traditional beliefs than just agricultural practice. Shifting cultivation was more preferable to the modified cropping cultivation because of the economic conditions and requires less labor for farming. The population of this area is on a steady rise causing high demand for agricultural land ultimately increasing forest cover loss. Further, loss in the forest cover is also influencing biodiversity and soil erosion in the study area.

3 Materials and methods

3.1 Generation of thematic layers using remote sensing and geographic information system (GIS)

In this study, the parameters used for the forest fire risk zone mapping are population density, elevation, slope, aspect, temperature, rainfall, wind speed, and land use/land cover (LULC) which has been derived from the earth observation satellite and ancillary data.

LULC map of the study area was prepared using Landsat 5 Thematic Mapper (TM) using supervised classification. Furthermore, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)-derived Digital Elevation Model (DEM) was acquired from the United States Geological Survey (USGS) Earth Explorer (www.earthexplorer.usgs.gov) with a resolution of 30 m for elevation, slope, and aspect purpose as well as monitoring the vulnerability of forest fire risk zone. However, meteorological datasets viz. temperature, rainfall, and wind speed were downloaded from Global Weather data (www.globalweather.tamu.edu) for 16 different meteorological stations which were present in the district and its neighboring areas. The monthly average of meteorological data was interpolated by the

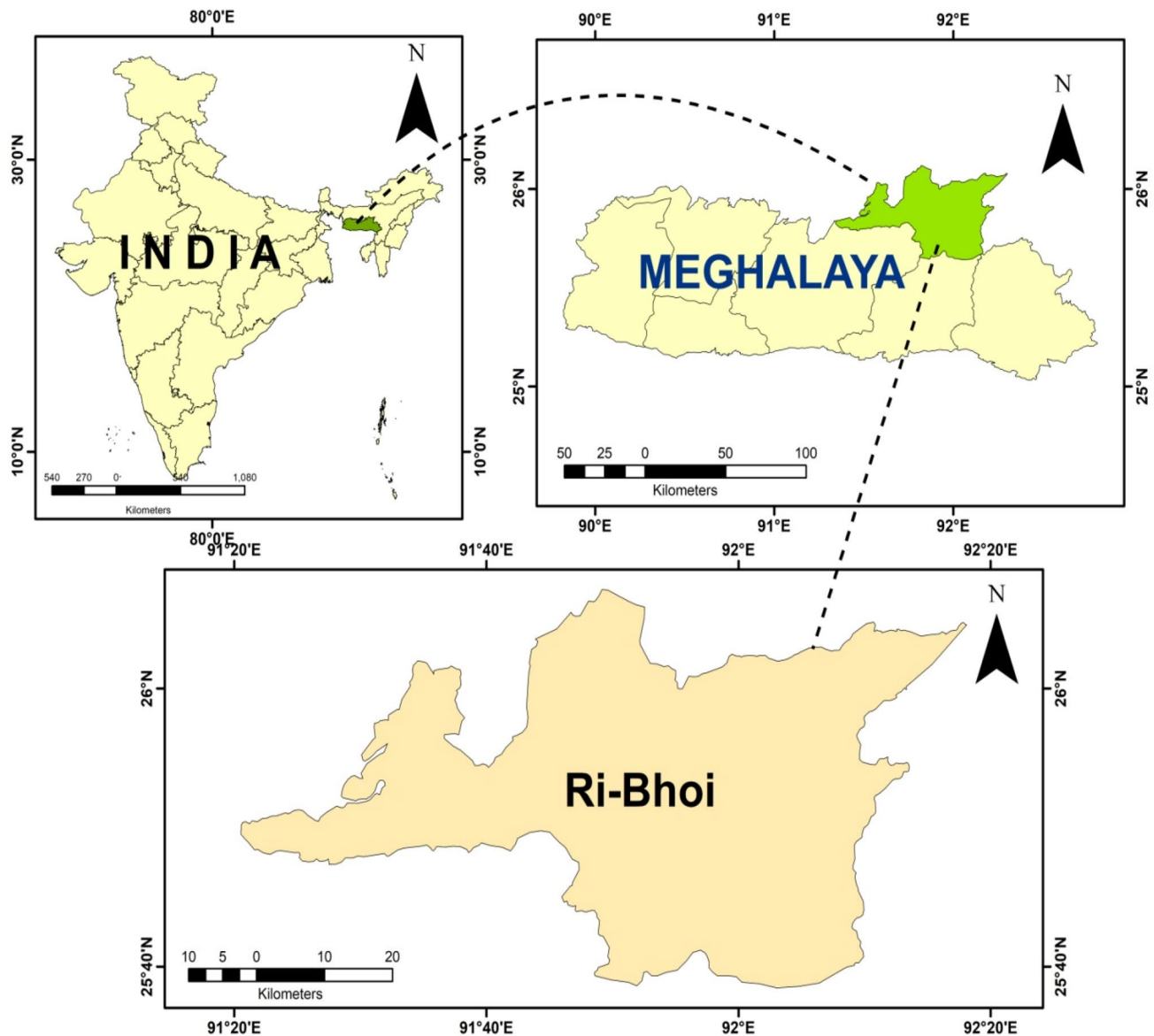


Fig. 1 Location of the study area

Inverse Distance weight method (IDW) method in the GIS environment. In addition, a population density map was generated from the census data [40] using a spatial interpolation tool through ArcGIS software. Subsequently, all the thematic layers were generated in raster format using the raster converter tool using ArcGIS. However, the overall methodology of the present study is shown in Fig. 2.

3.2 Assignment of weight to different thematic layer using AHP

Assessment of weight of each thematic layer is the most important for prediction of forest fire zone as output is mostly dependent on appropriate weight. Most important

methodologies were adopted for calculating weightage to delineate the fire risk zone such as fuzzy sets [41], linguistic variables [42], and AHP [43]. However, AHP is the most frequently used method for determining fire risk zone [16, 44]. AHP was a decision added method that generated relative ratio scales of paired comparison developed by Saaty [43]. In the present study, AHP-based pair-wise comparison matrixes were made between different thematic layers at each level of the hierarchy.

A pair-wise comparison matrix was made to compare all factors against each other based on their importance (equal, moderate, strong, very strong, and extremely strong). A standard Saaty's 1–9 scale was used to determine the relative importance values for all themes and

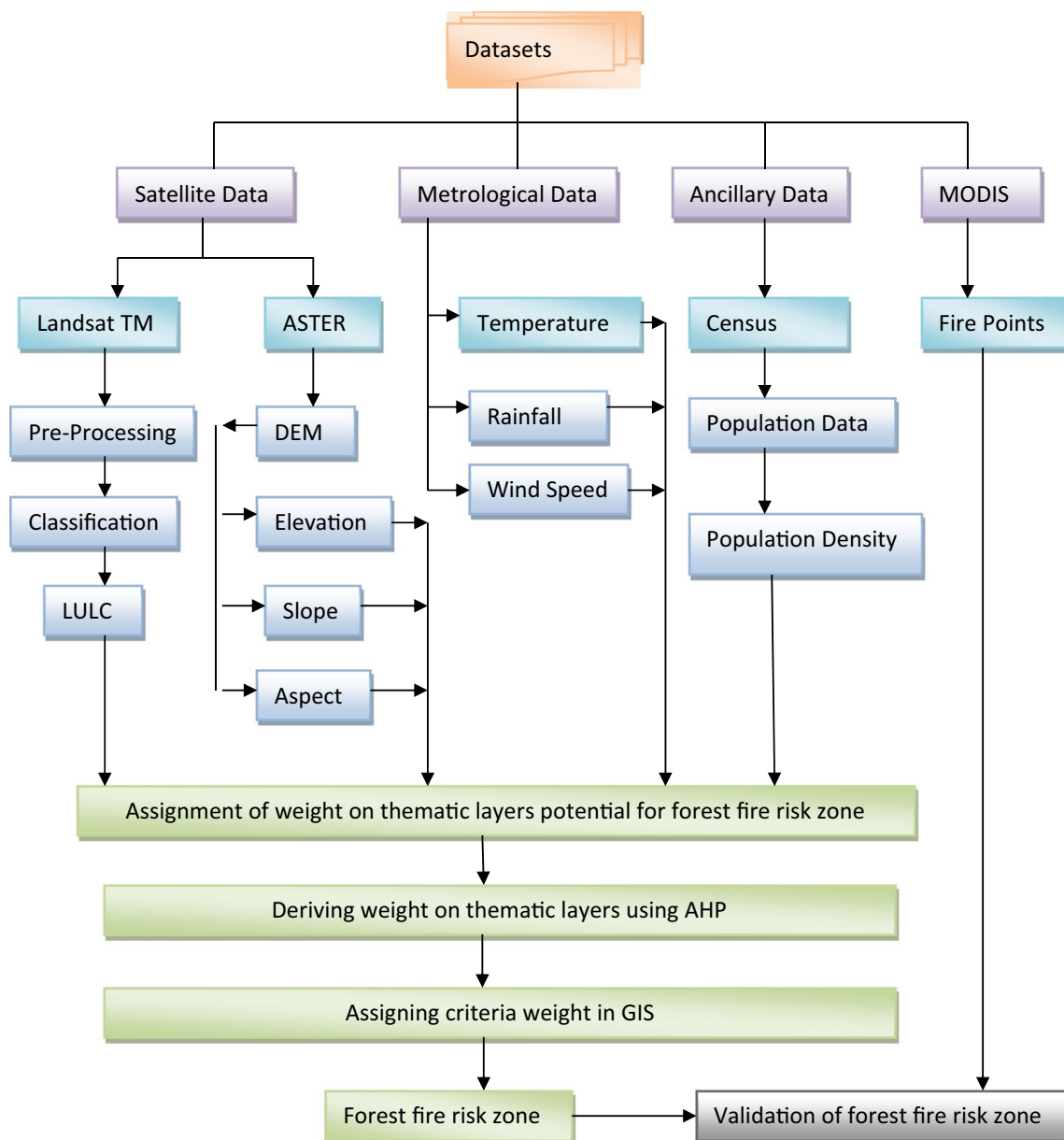


Fig. 2 Flowchart of methodology

their respective features, where value '1' denotes "equal importance" between the two themes, and the value '9' denotes the "extreme importance" of one theme compared to the other one shown in Table 1 [43]. The normalized relative weight was calculated by dividing each element of the pair-wise matrix by the sum of its column. The weights of each layer were decided using the principal eigenvector of the square matrix of each criterion. The higher was the weights the more was the influence of the parameters on the forest fire based on its relative importance.

The following equations were adopted to derive the weights of each of the thematic layers:

Table 1 Scale for a pair-wise comparison matrix

Intensity importance	Linguistic variables
1	Equal importance
2	Equal to moderate importance
3	Moderate importance
4	Moderate to the strong importance
5	Strong importance
6	Strong to the very strong importance
7	Very strong importance
8	Very to the extremely strong importance
9	Extreme importance

1. Sum the values in each column of the pair-wise comparison matrix using the formula (Table 5 in Appendix) (Eq. 1)

$$L_{ij} = \sum_{n=1}^n C_{ij} \tag{1}$$

where L_{ij} is the total column value of the pair-wise comparison matrix and C_{ij} is the criteria used for the analysis.

2. Divide each element in the matrix by its total row to generate a normalized pair-wise comparison matrix (Table 6 in Appendix) (Eq. 2).

$$X_{ij} = \frac{C_{ij}}{L_j} \tag{2}$$

where X_{ij} = normalized pair-wise comparison matrix.

3. Divide the sum of the normalized row of the matrix by the number of criteria/parameter (N) to generate the standard weight by using the following formula (Eq. 3):

$$W_{ij} = \frac{\sum_{j=1}^n X_{ij}}{N} \tag{3}$$

where W_{ij} = standard weight.

4. For calculating the consistency vector values, the following formula was used (Eq. 4):

$$\lambda = \sum_{i=1}^n CV_{ij} \tag{4}$$

where λ = consistency vector.

5. Consistency Index (CI) was used as a deviation or degree of consistency which was then calculated using the following formula (Eq. 5):

$$CI = \frac{\lambda - n}{n - 1} \tag{5}$$

where CI = Consistency Index, n = Number of criteria.

6. Consistency ratio (Cr) is calculated by using the formula (Eq. 6):

$$Cr = \frac{CI}{RI} \tag{6}$$

where RI = random inconsistency.

If the value of the Consistency ratio (Cr) is less than or equal to 0.10, then the inconsistency is acceptable. Random inconsistency (RI) values for 'n' number of criteria, i.e., number of parameters [43] (Table 2).

3.3 Assignment of weights for forest fire risk zone

The method of the weighted linear combination was applied to identify the forest fire risk zones. The weights of the different thematic layers were multiplied by the weights of features of each thematic layer and summed the products of all the attributes and obtained the total scores by using the formula (Eq. 7):

$$TS = \sum W \times R \tag{7}$$

where TS = Total Score, W and R were the weight of the thematic layers and the weight of the features in the thematic layers, respectively.

3.4 Validation of fire risk zone map using MODIS data

The accuracy of the fire risk zone map was verified using the fire point's data of MODIS satellite for 2011 which was acquired from National Remote Sensing Centre (NRSC), Indian Space Research Organisation (ISRO), Bhuvan. The fire points were overlaid to the forest fire risk zone map of the study area. The percentage of an area which was evaluated from the spatial analyst tool in GIS and imported to Microsoft Excel environment for calculating risk zone percentage by Eq. 8.

Then, the percentage (%) of the area under fire was calculated using the equation given as follows

$$\text{Percentage of an area(\%)} = \frac{\text{estimated area}}{\text{total area}} * 100 \tag{8}$$

4 Results and discussion

The analysis of forest fire risk zone in Ri-Bhoi district of Meghalaya was carried out using the eight parameters which include population density (PD), LULC, elevation

Table 2 Random inconsistency values [43]

n	2	3	4	5	6	7	8	9
RI	0	0.52	0.9	1.12	1.24	1.32	1.41	1.45

where n = number of criteria used and RI = Random Inconsistency

(EL), temperature (TEMP), slope (SL), aspect (AS), wind speed (WS), and rainfall (RF).

4.1 Population density

An increase in population density is one of the main reasons behind the number of fire incidents in a forested landscape. Forest fire in northeast India is mainly caused by shifting cultivation, i.e., slash and burn agriculture. Past research work also has discussed that rapid population growth promotes the short fallow cycle in shifting cultivation in northeast India [45–48]. Many other studies throughout the world have also used the importance of population density in forest fire monitoring and mapping [2, 16, 49].

In study area, population map has been categorized in four different classes, i.e., very high populated area (7658–16,809 persons/sq. km.), high populated area (2183–7058 persons/sq. km.), moderately populated area (470–2183 persons/sq. km.), and low populated area (9–470 persons/sq. km.) (Fig. 3). The final weightage for all subclasses is calculated and shown in Table 3.

4.1.1 LULC

LULC dynamics are mostly accelerated by human activities which caused many changes those affect various forests and environment ecosystem [50, 51]. Many previous kinds of research have focused on the importance of land cover

classes in evaluating the risk of a given area to fire events as it is related to fuel types and characteristics [16, 52–54].

In this study, LULC has been categorized into four different classes, i.e., forest land, agriculture/scrubland, settlement, and water body. Most of the fire areas were caused due to the slash and burnt of forest areas for cultivation purposes and forests such as very dense forest, dense forest, and the open forest have fallen under very high-risk zone which was accounted for 1417.06 sq. km. (57.89%) followed by agriculture/scrubland for 868.87 sq. km. (35.49%), settlement areas for 72.93 sq. km. (2.98%), and water bodies comprised of 89.14 sq. km. (3.64%) over the region. The scrubland was mainly due to the abandoned shifting cultivation of land (Fig. 4).

4.1.2 Elevation

Usually, a decreasing trend in forest fires is apparent with rising elevation due to lower temperatures and higher humidity as opposed to the regions at a lower elevation [55]. The elevation in the study area varied from 25 to 1358 m which was then reclassified into four classes, viz. low (25–364 m), moderate (364–583 m), high (583–821 m), and very high (821–1358 m), respectively, a map of which is presented in Fig. 5. It was found that forest fire incidents were mostly very high in numbers in the lower and moderate elevation ranges, whereas there were fewer fire incidents at high elevations in the study area. This can be attributed to the high moisture content in vegetation and

Fig. 3 Population density map of the study area

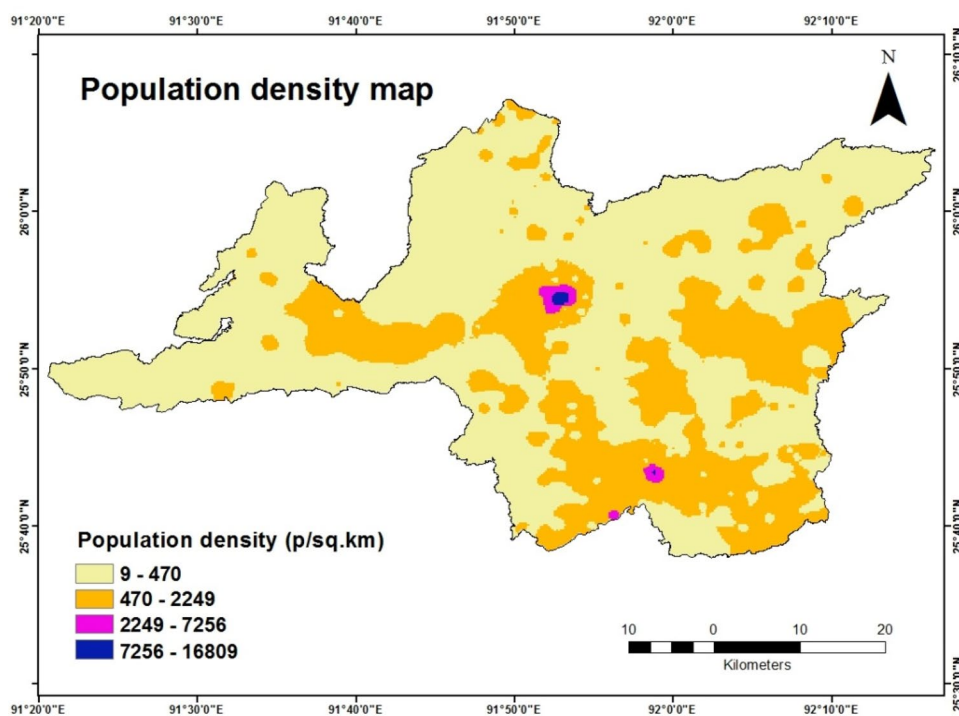


Table 3 Normalized and final weights of different features of the thematic layer for assessment of forest fire zone

Thematic layers	Normalized weight (%)	Subclasses	Final weight
Population density (person/km ²)	0.33	7658–16,809	0.19
		2183–7058	0.09
		470–2183	0.04
		9–470	0.02
Land use/land cover	0.23	Forest	0.13
		Agricultural/scrub-land	0.06
		Settlement	0.03
		Water bodies	0.01
Elevation (m)	0.15	25–364	0.09
		364–583	0.04
		583–821	0.02
		821–1358	0.008
Temperature (°C)	0.11	28–31	0.06
		27–28	0.03
		25–27	0.01
		23–25	0.006
Slope (degree)	0.07	45–61	0.04
		30–45	0.02
		15–30	0.008
		0–15	0.004
Aspect	0.06	SW, S	0.04
		NW, W	0.02
		E, SE	0.007
		NE, N, Flat	0.003
Wind speed (m/s)	0.04	1.32–1.42	0.02
		1.25–1.32	0.01
		1.19–1.25	0.004
		1.11–1.19	0.002
Rainfall (mm)	0.02	166–239	0.01
		239–301	0.005
		301–361	0.002
		361–428	0.001

soil which made it unfavorable for ignition and spread of fire. The final weights of different elevation layers were calculated using AHP (Table 3).

4.1.3 Temperature

Temperature played an important role in a forest fire. High temperature helped to the rising rate of evapotranspiration where the seasonal drying of fuel, such as needles, leaves, twigs, and dead trees, resulted in inappropriate conditions that were suitable for an explosion of fire [56]. The average monthly temperature varied from 23 to 31 °C. The study area with high temperature was mostly in border areas of the state of Assam. However, the fire incidents

were low because of low elevation ranges such as settlement areas, agricultural land, and less forest cover. The areas with low temperature were very few fire occurrences because of the moisture content present in fuel where the conditions were not very suitable for ignition of fire (Fig. 6).

4.1.4 Slope

The slope is an indicator of the rate of change of elevation. The rapid spread of fires usually moved faster uphill than downhill [55, 57]. The steeper slope helped to spread fire because fuel was more dried on the upper slope than the lower slope. In the present study, the slope tended to very undulating even in low slope areas. Slope map of the study area was prepared from Cartosat-1 DEM data in ArcGIS and was divided into four classes as low (0–15%), moderate (15–30%), high (30–45%), and very high (45–60%) (Fig. 7). The region where the fire was mostly seen in a low and moderate slope (0–30°) since a major portion of forest cover was found in these slope areas.

4.1.5 Aspect

Aspect can be described as the direction of the maximum rate of change in elevation between each cell and its neighbors. An eastern part of the slope gets more sunlight early in the morning than a slope with a west aspect. Also, the southern part of the slope gets more sunlight in the northern hemisphere, so the temperature on the southern side was high and fuel gets dry easily. The southern aspect received more sunlight at a very high risk of forest fire [58]. The study area was classified into four classes, i.e., north and northeast; east and southeast; south and southwest; west and northwest (Fig. 8).

4.1.6 Wind speed

Wind speed is one of the weather conditions behaviors which have a massive influence on the intensity and fire spread of an area [59–62]. Also, the high temperature and hot strong winds together put the area at high risk of fire [63]. The monthly average of wind speed in the study area was 1.11–1.32 m/s. The speed of the wind was mostly high in low and moderate elevation, whereas it was low in high elevation ranges. In the present study, the upper part of the study area was having high wind speed than the lower part (Fig. 9).

4.1.7 Rainfall

Generally, rainfall affects both the moisture content of the fuel and the soil. The areas with high rainfall were fewer fire incidents due to the high moisture content of

Fig. 4 Land use/land cover map of the study area

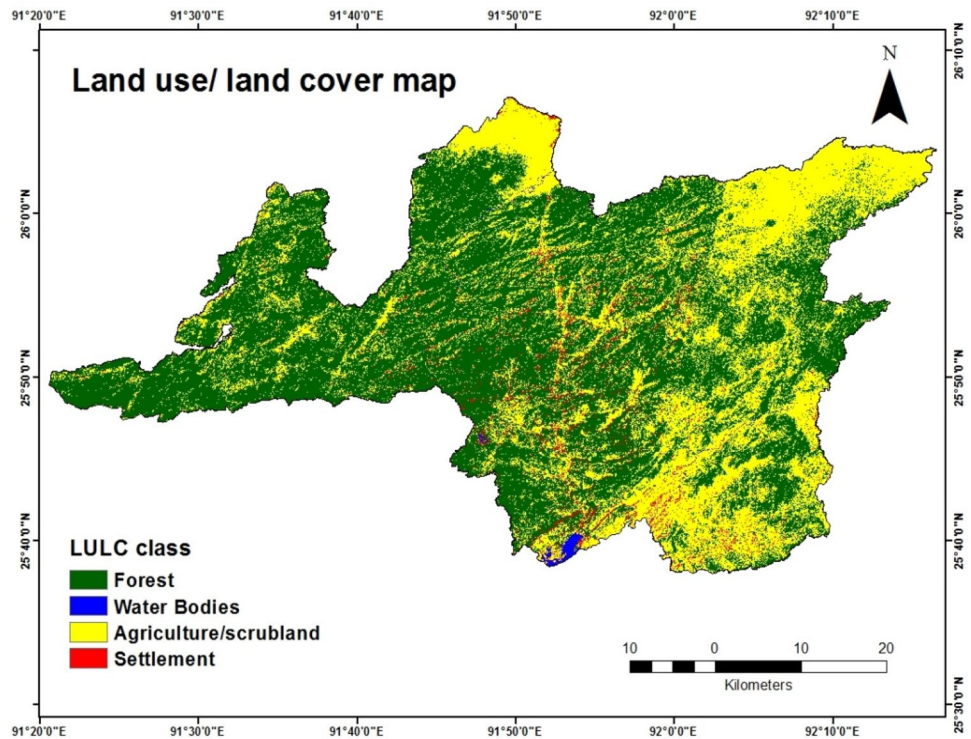
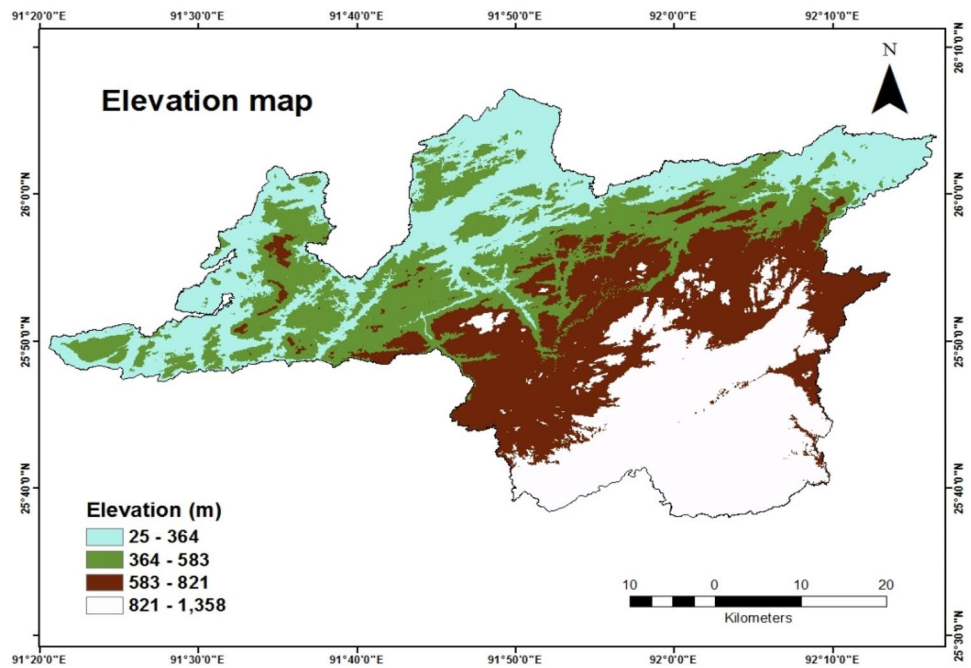


Fig. 5 Elevation map of the study area



the fuel. The amount and time of rainfall played a crucial role in the physiological growth of vegetation and influenced the formation of forest fire [64]. The monthly average of rainfall in the study area was 166–428 mm showed

higher elevation range caused ignition and spread of fire very low. There was a variation in rainfall concentration over the study area (Fig. 10).

Fig. 6 Temperature map of the study area

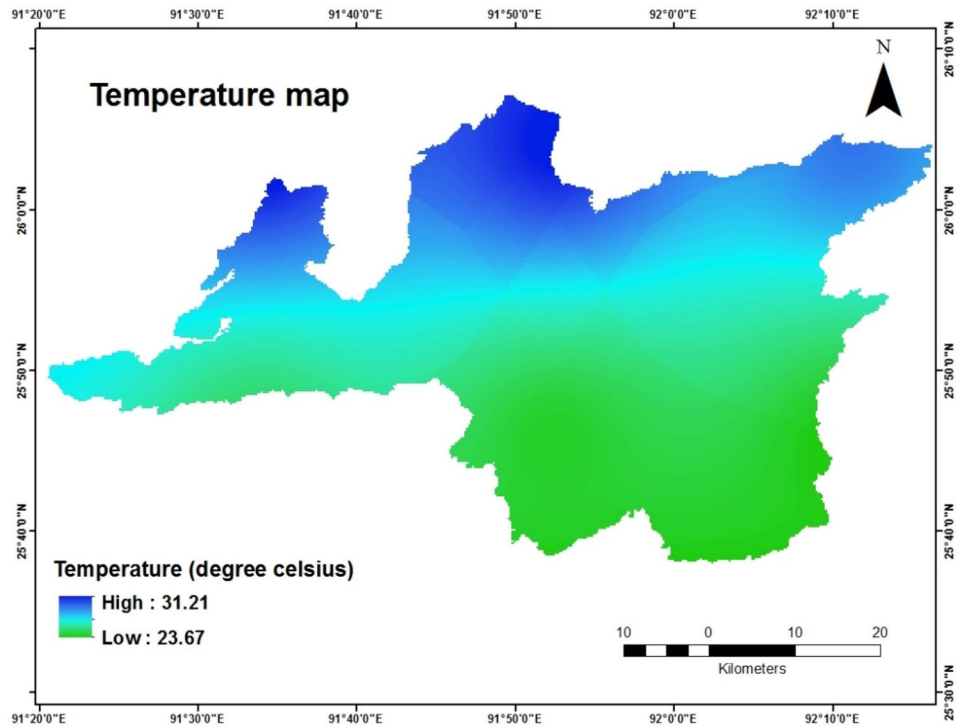
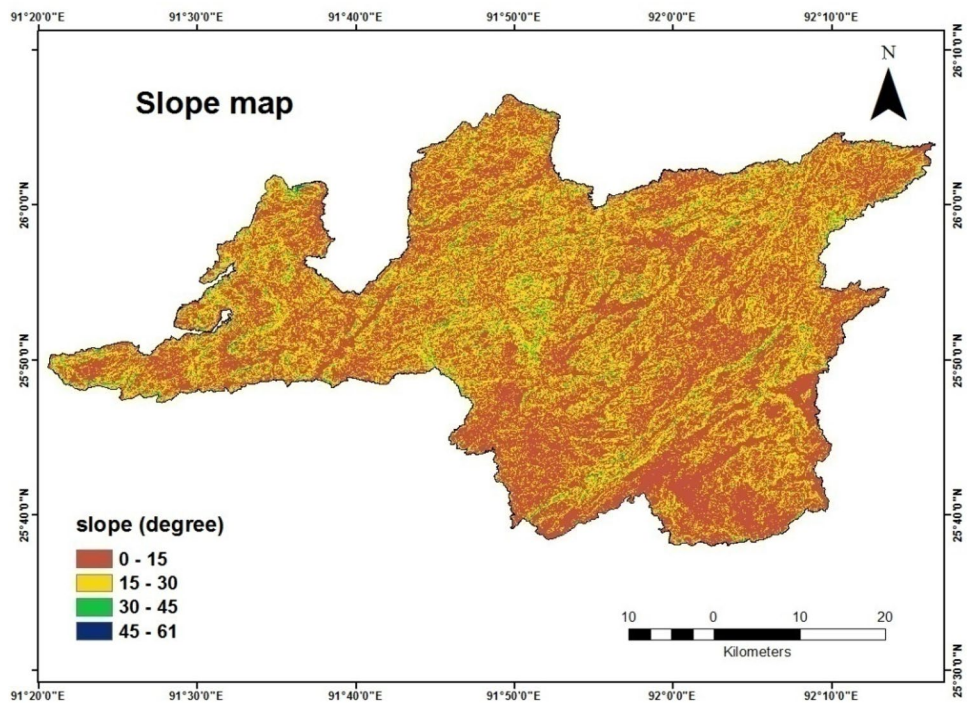


Fig. 7 Slope map of the study area



4.2 Evaluation of forest fire risk zone

The forest fire risk map was prepared by geospatial technology and the AHP method. After calculating the final weights of all parameters, it was converted to raster format and summed up using a raster calculator to demarcate the

forest fire potential risk zone in ArcGIS software. The total score was obtained and classified into four distinct zones, namely low (9–14), moderate (14–18), high (18–23), and very high (23–30). The fire zones map was further processed by applying a majority filter in ArcGIS to avoid/minimize pixel speckling. Area of 804.31 sq. km. (32.86%) came under a very

Fig. 8 Aspect map of the study area

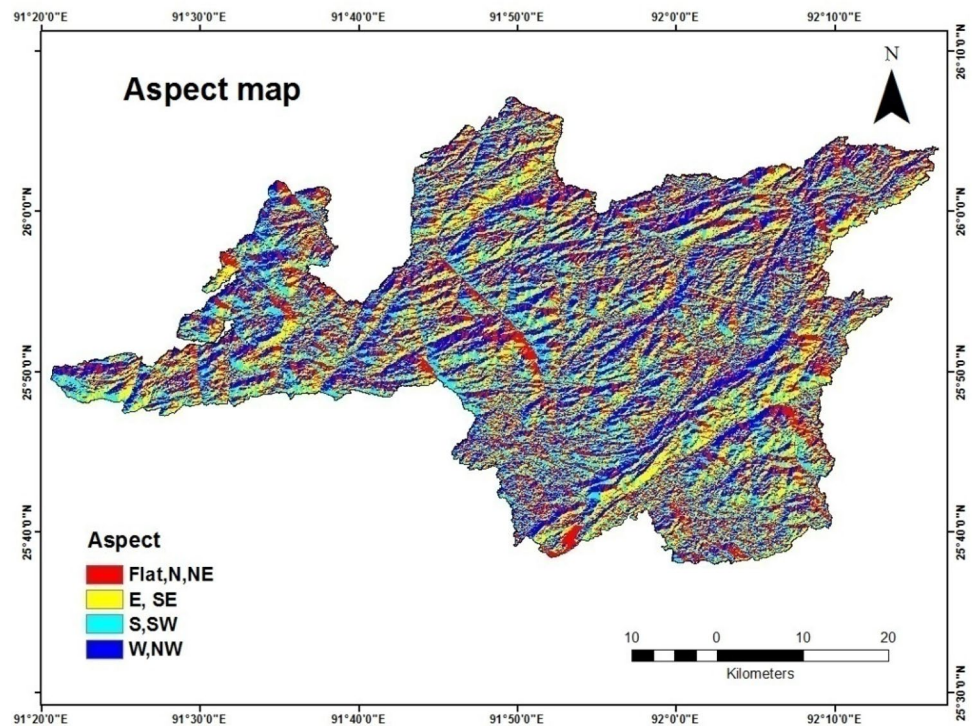
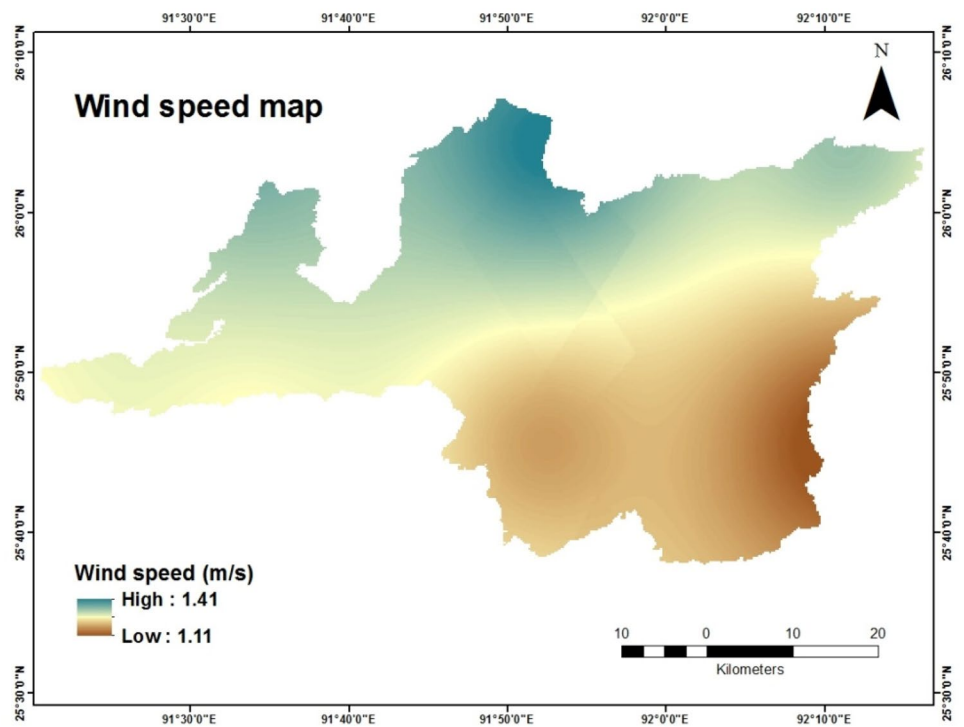
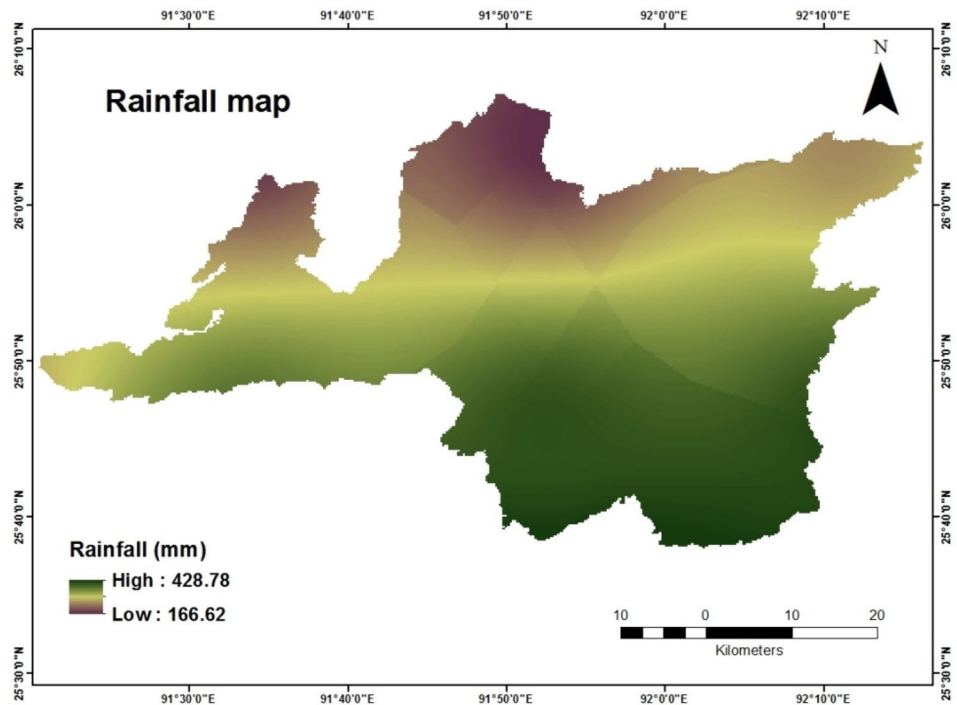


Fig. 9 Wind speed map of the study area



high fire susceptibility risk zone followed by 583.10 sq. km. (23.82%) under high risk, 670.47 sq. km. (27.39%), moderate risk and 390.12 sq. km. (15.93%) came under the low-risk category (Table 4). The potential areas for forest fires were mostly high in sparse population areas and concentrated

mostly in the eastern part of the district where agriculture practice was very high. In addition, very high fire susceptibility areas were found mostly in the low elevation ranges of low slope especially in the southern area of the study area (Fig. 11).

Fig. 10 Rainfall map of the study area**Table 4** Distribution of the forest fire risk zone

Fire risk zone	Area (sq. km)	Percentage (%)
Very high	804.31	32.86
High	583.10	23.82
Moderate	670.47	27.39
Low	390.12	15.93

4.3 Validation of the forest fire risk zone

The validation of the forest fire risk zone was verified by the fire points of MODIS satellite of the year 2011 which was acquired from NRSC (ISRO) (www.bhuvan.nrsc.gov.in). The fire was very prone in low to moderate elevation ranges and most of the fire points overlaid in the map were seen as very high-risk zone (Fig. 12).

5 Conclusion

Forest fires due to anthropogenic activity have been a major problem across tropical regions.

This study explores the application of geospatial technologies and the AHP method to assess fire risk in the Ri-Bhoi district of Meghalaya, India. In this study, parameters used for assessing fire risk are population, LULC, slope, aspect, elevation, temperature, rainfall, and wind speed. The final map of fire risk was categorized into four zones as very high, high, moderate, and low risk. Very high fire risk occupies 32.86% followed by high risk 27.39% and moderate risk 15.93% of the study area. Results obtained from this study could be useful for a local administrator to address broad-scale fire hazard concerns for future action. Additionally, the methodology adopted in this study can be applied to the tropical regions as well as another part of the NE region of India where a forest fire is a big problem.

Fig. 11 Forest fire risk zone map

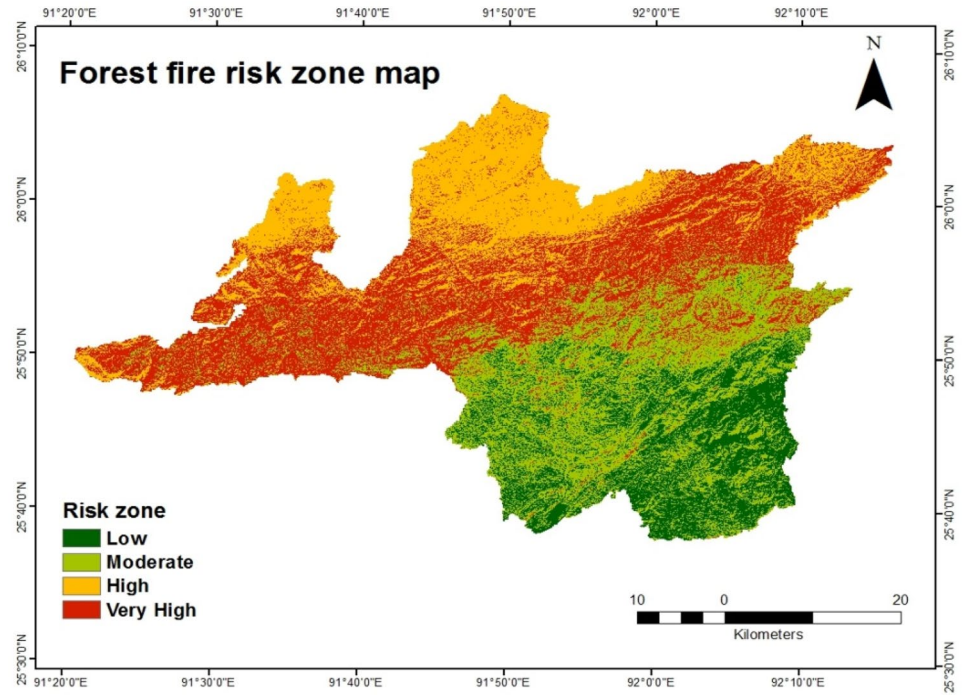
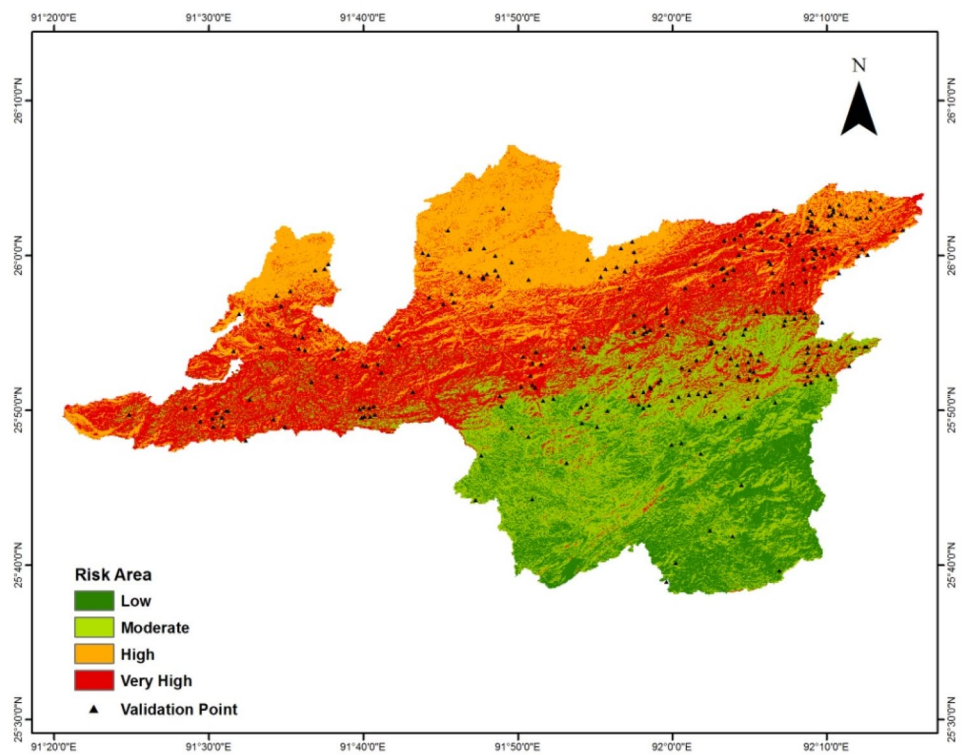


Fig. 12 Validation map of the forest fire risk zone



Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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Appendix

Table 5 Pair-wise comparison matrix of the thematic layers

	PD	LULC	EL	TEMP	SL	AS	WS	RF
PD	1	3	3	5	5	6	7	7
LULC	0.33	1	3	4	5	5	6	7
EL	0.33	0.33	1	3	3	4	5	5
TEMP	0.2	0.25	0.33	1	3	3	5	6
SL	0.2	0.2	0.33	0.33	1	2	3	7
AS	0.17	0.2	0.25	0.33	0.5	1	3	5
WS	0.14	0.17	0.2	0.2	0.33	0.33	1	5
RF	0.14	0.14	0.2	0.17	0.14	0.2	0.2	1
Total	2.51	5.29	8.31	14.03	17.97	21.53	30.2	43

Table 6 Normalized pair-wise matrix

	PD	LULC	EL	TEMP	SL	AS	WS	RF	Total weight	Nor. Weight
PD	0.40	0.57	0.36	0.36	0.28	0.28	0.23	0.16	2.64	0.33
LULC	0.13	0.19	0.36	0.29	0.28	0.23	0.20	0.16	1.84	0.23
EL	0.13	0.06	0.12	0.21	0.17	0.19	0.17	0.12	1.17	0.15
TEMP	0.08	0.05	0.04	0.07	0.17	0.14	0.17	0.14	0.86	0.11
SL	0.08	0.04	0.04	0.02	0.06	0.09	0.10	0.16	0.59	0.07
AS	0.07	0.04	0.03	0.02	0.03	0.05	0.10	0.12	0.46	0.06
WS	0.06	0.03	0.02	0.01	0.02	0.02	0.03	0.12	0.33	0.04
RF	0.06	0.03	0.02	0.01	0.01	0.01	0.01	0.02	0.17	0.02

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