FOREST FIRE RISK MAPPING FOR THE HIMALAYAN STATE UTTARAKHAND USING GOOGLE EARTH ENGINE

Asmita Basu[1*], Shailja Mamgain[2], Arijit Roy[2]
asmitabasu89@gmail.com, shailja309@gmail.com, arijitroy@iirs.gov.in

[1*]Indian Institute of Social Welfare & Business Management, Kolkata, India
[2]Indian Institute of Remote Sensing, Indian Space Research Organization (ISRO), Dehradun, India

KEY WORDS: Forest fire, Climate change, Risk mapping, Himalaya, Geographic Information System, Remote Sensing, Google Earth Engine

ABSTRACT

Climate change has exacerbated the intensity as well as frequency of forest fire events in the Indian state of Uttarakhand. The present study focusses on undertaking forest fire risk mapping across the state by utilizing geospatial technology along with Google Earth Engine. Ten parameters were identified that have a strong influence in determining fire prone areas. The Analytic Hierarchy Process (AHP) was then implemented for the development of the risk map in which criteria weights were assigned to the parameters based on their ability to influence a forest fire event. The analysis revealed that out of the total forest area, 24.22% is under 'very high' risk zone, 29.24% is under 'high' risk zone, 18.23% is under 'moderate' risk zone, 7.69% is under 'low' risk zone and 20.62% is under 'very low' risk zone of forest fire. Further study was carried out to determine fire risk levels in populated regions and in some of the most critical nature reserves having high ecological importance which reveals that 'very high' and 'high' risk zones have greater population density indicating the influence of anthropogenic activities on forest fire occurrence. The results additionally indicate that four national parks and wildlife sanctuaries are particularly vulnerable to forest fires at present which is a source of concern and requires intervention from the stakeholders.

1. INTRODUCTION

Forest fire or wildfire is a phenomenon that can be referred to as the unplanned and uncontrolled burning of forests and is a major cause behind deterioration of forest ecosystem (Jaiswal et al., 2002). Nearly 53 % of the forest cover of India is affected by fire, and such incidents are more alarming in the Central Himalayan region (Chavan et al., 2012). In the recent times, anthropogenic activities can be held responsible for 90% of the forest fire incidents. The impact of forest fire is intensified by climate change since high land surface temperature can provide favorable conditions for fire occurrence. A wildfire is a result of combined interaction between the different physical, biological, social and meteorological components. All these factors together determine the likelihood, extent and outcome of a forest fire incident.

Various attempts have been made to generate the forest fire risk maps using different methods. Jaiswal et al. (2002) integrated different factors responsible for forest fire in the GIS environment to generate forest fire risk map. The map was prepared by assigning subjective weights to classes of each layer based on their capability to induce fire and four levels of fire risk were derived from very high to low. Erten et al. (2004) used satellite imageries and land use information to assess the fire risk in the Mediterranean countries. The fire spread model was implemented to find the shortest possible way of intervention and assess the areas that are required to be vacant due to fire risk. Chandra, (2005) applied remote sensing and GIS technology to assess forest fire risk in the Garhwal region of Himalayas.

The Analytic Hierarchy Process (AHP) technique was used to classify the region in different forest fire risk levels. The result was verified by ground truth and a comparison was then drawn with fire incidences of previous years. Chavan et al. (2012) utilized AHP technique for decision making in order to perform forest fire risk mapping in the Huynial watershed region of Tehri Garhwal district of Uttarakhand. Ghobadi et al. (2012) used AHP to develop a forest fire prediction model for risk zone mapping of Golestan province, Iran. Babu.et al. (2016) utilized different satellite imageries for developing the Forest Danger model to precisely predict the forest fire risk in Uttarakhand state. Pandey & Ghosh (2018) applied AHP in order to generate forest fire risk map from fire risk models for the district of Pauri Garhwal, Uttarakhand.

The present study attempts to develop a comprehensive methodology for forest fire risk zone mapping for Uttarakhand using the AHP by identifying the primary environmental variables and other factors that influence the forest fires through thorough literature review. AHP is used for decision making by involving multiple criteria that are structured into a hierarchy. The study area has been classified into different categories based on the levels of forest fire risk from which the final forest fire risk map for the entire state is generated. This study explores the capabilities of remote sensing and GIS techniques in order to suggest an appropriate methodology for forest fire risk zone mapping. Such maps will help forest department officials prevent or minimize fire risk activities within the forest and take necessary actions when fire breaks out (Chuvieco & Sales, 1996).

* Corresponding author

https://doi.org/10.5194/isprs-archives-XLVIII-M-3-2023-27-2023

2. MATERIALS AND METHOD

2.1 Study area

The Himalayan state of Uttarakhand has been chosen as the area of interest for the study (Figure 1). The state is located in northern part of India bounded by China in the north and Nepal in the east. It extends from 28^0 44' & 31^0 28' N Latitude and 77° 35' & 81° 01' E Longitude. The state is majorly covered by hilly topography dominated by snow cover and steep slopes and covers an area of 53483 sq. km. The northern part of the sate constitutes the Himalayan range and glaciers. Uttarakhand can be primarily divided into two regions- Garhwal and Kumaon. The Garhwal region mainly comprises of 7 states which includes Uttarkashi, Chamoli, Pauri Garhwal, Rudraprayag, Tehri Garhwal, Dehradun and Haridwar. The other 6 districts fall under the Kumaon region including Udham Singh Nagar, Nainital, Almora, Pithoragarh, Champawat and Bageshwar. The natural forest cover in Uttarakhand constitutes 45.44% of its total geographical area which has been divided into three types: Very dense forest (VDF), Moderately dense forest (MDF) and Open forest (OF) and the remaining area consists of scrub (ISFR, 2021).

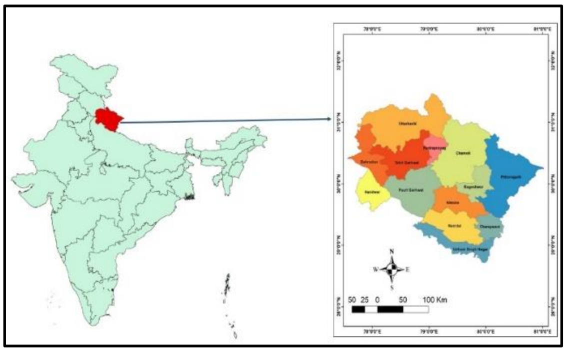

Figure 1 Study Area Map

2.2 Dataset used

Forest fire risk zone mapping in Uttarakhand was done using different satellite-derived products and indices. The parameters that were taken into account for undertaking the study along with corresponding datasets used are as follows:

Parameter	Database	Data Type
Normalize Difference Vegetation Index	Sentinel 2	Spectral Data
Normalize Difference Moisture Index	Sentinel 2	Spectral Data
Elevation	SRTM	DEM
Slope	SRTM	Generated using DEM
Aspect	SRTM	Generated using DEM
Forest Density	Sentinel 2	Generated using NDVI
Distance from settlements	Open Street Maps	Vector
Distance from roads	Open Street Maps	Vector
Land Use/ Land Cover	MODIS	LULC
Land Surface Temperature	MODIS	Raster

Table 1. Datasets utilized for different parameters

The time period for the study has been taken from March to June which is the forest fire season in the state (Babu et al., 2016). In the study, majority of the datasets associated with the different parameters have been retrieved and computed using the Google Earth Engine (GEE) which were then analysed further in the ArcGIS software. GEE is a cloud based platform which is used by researchers and other organizations around the globe for performing geospatial analysis. A wide range of satellite imageries are available to download at free of cost through JavaScript programming in the GEE environment. 8 out of 10 layers in the study have been generated from GEE in raster format and the rest 2 layers i.e. distance from roads and settlement layers have been downloaded from Open Street Maps (Geofabrik) in vector format.

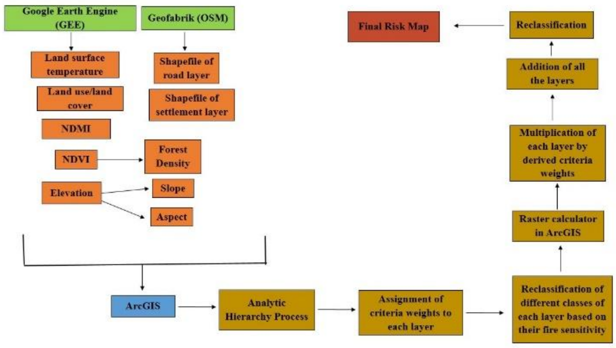

Figure 2. Flowchart of the methodology followed for the generation of final risk map

2.3 Analytic Hierarchy Process

Ten parameters have been considered in the study to assess the fire risk zones in Uttarakhand that have influence over fire behavior. The Analytic Hierarchy Process or AHP has been used to carry out the analysis. AHP was developed by Thomas L. Saaty in the 1970s and it is a widely used method which combines mathematics and psychology. The method has been extensively utilized for multi criteria decision making (MCDM) which can be defined as taking decision about solving a particular objective when there is involvement of multiple criteria.

3. RESULT AND DISCUSSION

A fire risk zone can be defined as an area from where a fire begins and spreads to surrounding areas. Ten parameters that were considered to assess the influence of both the natural and anthropogenic factors on fire behavior have been reclassified based on their sensitivity to fire, derived from available literature (Jaiswal et al., 2002; Chavan et al., 2012). Forest Fire Risk Maps (FFRM) were generated for each parameter by utilizing the GIS environment.

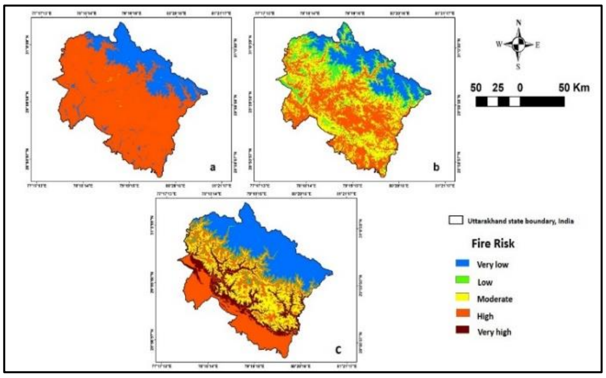

Figure 3 FFRM for (a) NDVI_max, (b) NDMI, (c) Elevation

NDVI_Max or vegetation index is a crucial parameter for the identification of forest areas. A pixel's vegetation is likely to be dense and may even comprise a forest if there is substantially more reflected near-infrared radiation than visible radiation. Later, research has demonstrated a clear correlation between the NDVI and the ability of plant canopies to capture energy (Ghobadi et al., 2012). The NDMI or moisture index on the other hand refers to the amount of moisture stored in the plants. A period of low humidity will result in lower values of NDMI increasing the probability of a fire outbreak in forest. Since the terrain of Uttarakhand is hilly and irregular, elevation affects land surface temperature (LST) which declines as elevation increases thereby influencing the fire behavior (Jaiswal et al., 2002). Figure 3 (a) represents the risk level of forest fire in NDVI_max map. The NDMI map [3 (b)] indicates that the northern part of the state has 'very low' fire risk whereas major portion in the central and southern part of the state has 'high' risk of forest fire with very little area falling under 'moderate' risk zone. In the NDMI map, the northern hilly terrain of the state primarily has 'low' to 'very low' fire risk whereas most of the area faces 'moderate' to 'high' fire risk southwards. Figure 3 (c) reveals that the categorization of fire risk levels based on elevation varies uniformly having 'very low' risk in the north, primarily 'moderate' risk in the central part of the state with very little area facing 'high' risk. The areas further down are vulnerable to 'very high' fire risk whereas the extreme south faces 'high' fire risk.

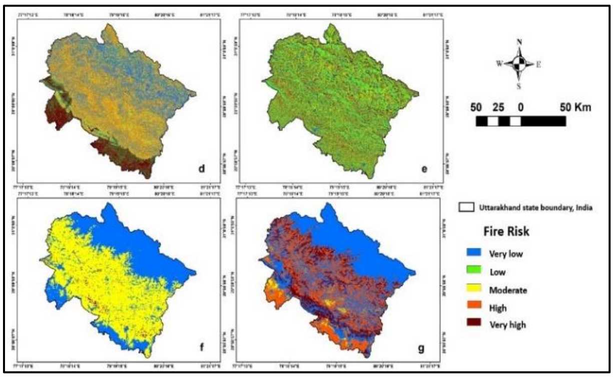

Figure 4. FFRM for Slope (a), Aspect (b), Forest density (c), Land use/Land cover (d)

Slope plays a crucial role in influencing the fire pattern. The pace of burning and the rate at which a small fire spreads in the forest are both considerably accelerated by steep slopes. It is important to consider the aspect parameter since rate at which vegetation dries out is intimately linked with rate of fire spread. The amount of sunshine a specific region receives depends on the slope's direction. As they receive more sunlight than North Slope, South and West Slopes are significantly warmer and drier becoming more vulnerable to a fire occurrence (Chavan et al., 2012). Forest density directly influences forest fire since area having higher percentage of closely packed trees will provide the fuel for rapid spread of fire. Land use/land cover map provides significant information about the landscape of an area which helps to identify fire prone areas based on fire hotspot data of last few years. Figure 4 (a) represents risk map for slope revealing that southernmost part of the state faces 'very high' risk of forest fire followed by 'high', 'moderate' and 'low risk' areas moving upwards and finally 'very low' risk zone comprising majority of the area in the northern part. The aspect risk map in figure 4 (b) shows majority of the portion under 'low' risk zone with very little area categorized under 'very low', 'moderate' and 'very high' risk zones. Figure 4 (c) reveals that in forest density risk map, the majority of the area in northernmost and southernmost part of the state fall under 'very low' risk zone whereas the central portion faces 'moderate' risk with very few patches of land under 'very high' risk zone. The risk map for land use/land cover has been depicted in figure 4 (d) which indicates the northernmost and southernmost parts of the state facing 'very low' and 'high' forest fire risk respectively. However, the majority of the forest area in the central portion of the state is susceptible to 'very high' fire risk having patches of area with 'moderate' and 'high' risk.

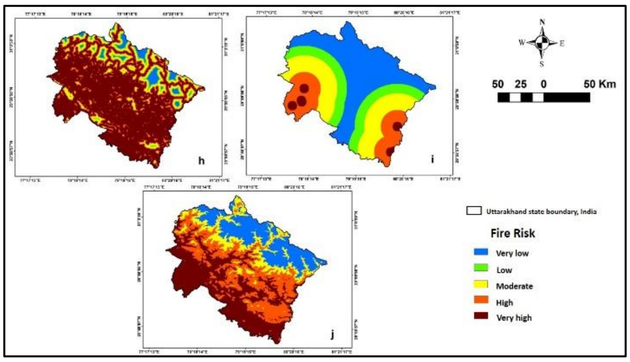

Figure 5. FFRM for Proximity to roads (a), Proximity to settlement area (b), Land surface temperature (c)

Proximity to roads and settlement areas need to be factored for the evaluation of fire prone areas as they can be potential sources of human induced fires which in turn can take the shape of large scale forest fire (Jaiswal et al., 2002). Land surface temperature (LST) can be assumed to be one of the most crucial parameters since high temperature creates drier environment that is favorable for a fire incident to occur. Figure 5 (a) represents the risk map of proximity to roads which indicates that major portion of the state is having 'high risk' of forest fire and as we move towards the northern part, the fire risk becomes 'high' to 'very low'. Risk map of proximity to settlement area depicted in figure 5 (b) shows few portions of area falling under 'very high' risk zone followed by 'high', 'moderate', 'low' and 'very low' risk areas. The risk map for land surface temperature [5 (c)] shows the risk level changing northward from 'very high' to 'very low.'

Rank	Parameter	Weight (%)
1	Land Surface Temperature	37.8
2	Land Use/ Land Cover	20.24
3	Distance from roads	9.41
4	Distance from settlements	9.14

5	Forest Density	6.18
6	Slope	4.32
7	Aspect	4.23
8	Elevation	3.48
9	NDMI (moisture)	2.81
10	NDVI_max	2.2

Table 2. Ranking of the parameters based on their degree of importance to influence forest fire

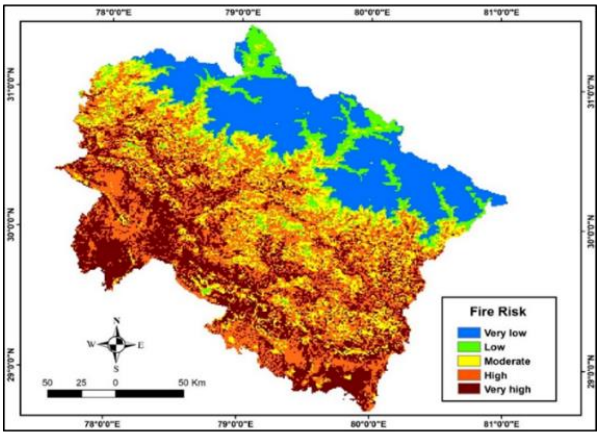

Figure 6. Different levels of forest fire risk in Uttarakhand state

Table 3 indicates the total area in Uttarakhand state falling under different levels of forest fire risk which has been derived from figure 6. It can be observed that highest percentage of area falls under 'high' risk zone followed by 'very high' 'very low' and 'low' risk zones respectively. District wise analysis reveals that majority of the 'very high' risk zone falls under Haridwar (71.3%), Dehradun is where the majority of the "high" risk zone is situated (50%), Significant portion of the "moderate" risk zone is located in Rudraprayag (29.5%), Uttarkashi has the maximum area under "low" risk zone (38.12%) and most of the area in Pithoragarh falls under "very low" risk zone (46.1%).

Total area (sq.km): 53326		
Risk level	**Area (sq.km)**	**Percentage (%)**
Very low	**10995**	**20.62**
Low	**4101**	**7.69**
Moderate	**9723**	**18.23**
High	**15594**	**29.24**
Very high	**12913**	**24.22**

Table 3. Distribution of area under each risk zones

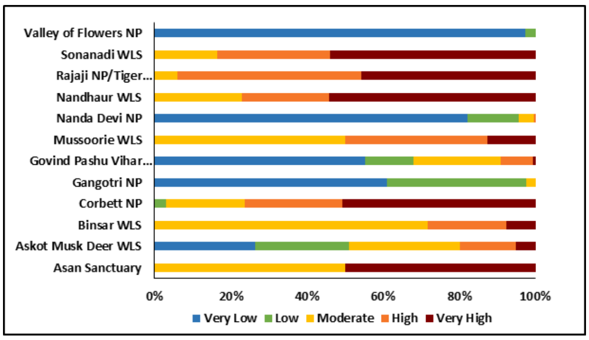

Figure 7. Risk zonation of Nature Reserve

The graph (figure 7) shows that in 5 out of 12 nature reserves, 50% or more area is under 'high' to 'very high' risk zones. Rajaji national park faces maximum problem of forest fire with more than 94.08% area highly susceptible to fire event followed by Sonanadi Wildlife sanctuary (83.66%), Nandhaur wildlife sanctuary (77.05%), Corbett national park (76.25%) and Asan sanctuary (50%).

Correlation of fire risk with population density

Population density can be defined as the number of individuals per unit area. In the present study, an attempt has been made to understand the relation between population density and forest fire risk. A densely populated area can increase the probability of human induced fire event. For the analysis, the population layer was downloaded from Global Human Settlement Layers (GHSL) which provides the data of population in each grid. The calculation has been done in ArcGIS by first extracting the shapefile of the different risk zones and then by calculating the average population density for each of the risk zones through the utilization of 'zonal statistics' tool. The analysis of distribution of average population density in different fire risk zones of Uttarakhand (Table 4) indicates that the average population density is almost nil in areas under 'very low' fire risk zone, slightly more in 'low' risk zone which increases by almost 20 times in areas that are classified under 'moderate' risk zone. The average population density value is double in 'high' risk areas and is slightly lower but almost equal to the former in the 'very high' risk zone. This proves the significance of influence of human interference on occurrence and spread of a forest fire. On the contrary, the study also indicates the need to chalk out suitable mitigation measures and quick response strategy in case of a fire outbreak in forest since evacuation in populated areas during a forest fire may pose a major challenge to the concerned authorities.

Risk level	**Average population density (persons/sq.km)**
Very low	**0.01**
Low	**0.1**
Moderate	**2**
High	**4**
Very high	**3.76**

Table 4: Distribution of average population density in different risk zones

5. CONCLUSION

Determination of fire prone areas was done by factoring both natural and anthropogenic parameters namely vegetation health, moisture index, forest density, land surface temperature, land use/land cover pattern, elevation, slope, aspect, distance from roads and settlements. The approach of AHP was adopted to calculate the subjective weights of each parameter to understand their degree of influence on fire occurrence. Through AHP, the relative weights obtained indicate that land surface temperature and land use/land cover parameters together hold more than 50% weightage in influencing a forest fire event. Five categories of risk were derived in the study from very low to very high based on fire sensitivity and fire inducing capability of each parameter. Classes of each layer were given a rank based on their fire sensitivity. The layers were then integrated in a GIS platform for the generation of fire vulnerability map of each layer. Each of the layers were then multiplied by their respective criteria weights derived from AHP method and then the 10 layers were combined in ArcGIS to produce the final risk map of Uttarakhand. The risk map showed 24.22% area is under 'very high' risk zone, 29.24% of the area is under 'high' risk zone, 18.23% under 'moderate' risk zone, 7.69% under 'low' risk zone and 20.62% under 'very low risk zone.

The average population density recorded in 'high' and 'very high' risk zones was much higher as compared to other areas indicating influence of humans over initiation of forest fire. Study was carried out to determine risk levels in some of the most critical nature reserves having high ecological importance. Result indicates that four national parks/wildlife sanctuaries are highly vulnerable to forest fire at present which is of major concern and the issue needs to be addressed by the stakeholders.

REFERENCES

Babu, S., Roy, A., & Prasad, P. R. (2016). Forest fire risk modeling in Uttarakhand Himalaya using TERRA satellite datasets. *European Journal of Remote Sensing*, *49*(1), 381-395. https://doi.org/10.5721/EuJRS20164921

Banerjee, P. (2021). MODIS-FIRMS and ground-truthing-based wildfire likelihood mapping of Sikkim Himalaya using machine learning algorithms. *Natural Hazards*, 1-37. https://doi.org/10.21203/rs.3.rs-750123/v1

Boroushaki, S., & Malczewski, J. (2008). Implementing an extension of the analytical hierarchy process using ordered weighted averaging operators with fuzzy quantifiers in ArcGIS. *Computers & geosciences*, 34(4), 399-410. https://doi.org/10.1016/j.cageo.2007.04.003

Chandra, S. (2005). Application of remote sensing and GIS technology in forest fire risk modeling and management of forest fires: A case study in the Garhwal Himalayan region. In *Geo-information for Disaster management*. 1239-1254.

Chavan, M.E., Das, K.K., & Suryawanshi, R.S. (2012). Forest fire risk zonation using Remote Sensing and GIS in Huynial watershed, Tehri Garhwal district, UA. *International Journal of Basic and Applied Research*. 02, 6-12. https://www.researchgate.net/publication/273035907_Forest_fire_risk_zonation_using_Remote_Sensing_and_GIS_in_Huynial_watershed_Tehri_Garhwal_district_UA

Chuvieco, E., & Salas, J. (1996). Mapping the spatial distribution of forest fire danger using GIS. *International Journal of Geographical Information Systems*. 10(3), 333-345.

Dong, X., Li-min, D., Guo-fan, S. et al. Forest fire risk zone mapping from satellite images and GIS for Baihe Forestry Bureau, Jilin, China. Journal of Forestry Research 16, 169–174 (2005). https://doi.org/10.1007/BF02856809

Erten, E., Kurgun, V., & Musaoglu, N. (2004, July). Forest fire risk zone mapping from satellite imagery and GIS: a case study. In *XXth Congress of the International Society for Photogrammetry and Remote Sensing, Istanbul, Turkey* (pp. 222-230).
https://www.researchgate.net/publication/228608573_Forest_Fire_Risk_Zone_Mapping_From_Satellite_Imagery_And_GIS_A_Case_Study

Fulé, P. Z., Garkoti, S. C., & Semwal, R. L. (2021). Frequent burning in chir pine forests, Uttarakhand, India. *Fire Ecology*, *17*(1), 1-11. https://doi.org/10.1186/s42408-021-00106-3

Forest Survey of India. (2021). India State of Forest Report 2021.

Joseph, S., Anitha, K., & Murthy, M. S. R. (2009). Forest fire in India: Areview of the knowledge base. *Journal of forest research*, 14(3), 127-134. http://dx.doi.org/10.1007/s10310-009-0116-x

Ghobadi, G. J., Gholizadeh, B., & Dashliburun, O. M. (2012). Forest fire risk zone mapping from geographic information system in Northern Forests of Iran (Case study, Golestan province). *International Journal of Agriculture and Crop Sciences*, *4*(12), 818-824.

Giglio, L., Schroeder, W., Hall, J., & Justice. (2018). MODIS Collection 6 Active Fire Product User's Guide Revision B. The National Aeronautics and Space Administration (NASA).

González, J. R., Palahí, M., Trasobares, A., & Pukkala, T. (2006). A fire probability model for forest stands in Catalonia (north-east Spain). *Annals of Forest Science*, 63(2), 169-176. http://dx.doi.org/10.1051/forest:2007047

Jaiswal, R. K., Mukherjee, S., Raju, K. D., & Saxena, R. (2002). Forest fire risk zone mapping from satellite imagery and GIS. *International journal of applied earth observation and geoinformation*, *4*(1), 1-10. http://dx.doi.org/10.1016/S0303-2434(02)00006-5

Malik, T., Rabbani, G., & Farooq, M. (2013). Forest fire risk zonation using remote sensing and GIS technology in Kansrao Forest Range of Rajaji National Park, Uttarakhand, India. India. Inter. J. of advanced RS and GIS, 2(1), 86-95.

Negi, G. C. S. (2019). Forest fire in Uttarakhand: causes, consequences and remedial measures. International Journal of Ecology and Environmental Sciences, 45(1), 31-37.

National Aeronautics and Space Administration & National Geospatial-Intelligence Agency. (2015).The Shuttle Radar Topography Mission (SRTM) Collection User Guide.

National Aeronautics and Space. (2018). NASA VIIRS Land Science Investigator Processing System (SIPS) Visible Infrared Imaging Radiometer Suite (VIIRS)
375 m & 750 m Active Fire Products Product User's Guide Version 1.4.

NASA Near Real-Time and MCD14DL MODIS Active Fire Detections (SHP format). Dataset. Available online https://www.earthdata.nasa.gov/learn/find-data/near-real-time/firms/active-fire-data

Pandey, K., & Ghosh, S. K. (2018). Modeling of parameters for forest fire risk zone mapping. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, *42*, 299-304. http://dx.doi.org/10.5194/isprs-archives-XLII-5-299-2018

Pant, H. (2017). Case study of Uttarakhand in perspective of extreme climatic events: fire, ecosystem and livelihoods.

In *Climate Change Research at Universities* (pp. 519-531). Springer, Cham.

Pant, M. (2019). Forest Fire-A Case Study on the Four National Park of Uttarakhand. *International Journal of Engineering Research & Technology (IJERT)*, 8(65). http://www.ijert.org

Ramm, F. (2022). OpenStreetMap Data in Layered GIS Format

Singh, R. D., Gumber, S., Tewari, P., & Singh, S. P. (2016). Nature of forest fires in Uttarakhand: frequency, size and seasonal patterns in relation to pre-monsoonal environment. *Current Science*, 398-403. https://www.jstor.org/stable/24908631

Sonawane, K. R., & Bhagat, V. S. (2017). Improved change detection of forests using Landsat TM and ETM+ data. *Remote Sensing of Land*, 1(1), 18-40. http://dx.doi.org/10.21523/gcj1.17010102

Satendra and Kaushik, A.D. (2014): Forest Fire Diaster Management. National Institute of Disaster Management, Ministry of Home Affairs, New Delhi.

Sulla-Menashe, D & Friedl,M. (2018). User Guide to Collection 6 MODIS Land CoverMCD12Q1 and MCD12C1) Product.

Schiavina M., Freire S., MacManus K. (2022): GHS-POP R2022A - GHS population grid multitemporal (1975-2030).European Commission, Joint Research Centre (JRC)Wan, Z. (1999). MODIS Land-Surface Temperature Algorithm Theoretical Basis Document (LST ATBD). https://doi.org/10.2905/D6D86A90-4351-4508-99C1-CB074B022C4A

APPENDIX

Districts	MODIS	VIIRS
Dehradun	77	580
Haridwar	99	590
Chamoli	170	1377
Pauri-Garhwal	580	4873
Tehri	335	2720
Uttarkashi	78	565
Rudraprayag	22	196
Almora	238	2187
Pithoragarh	145	1578
Bageshwar	51	676
Champawat	221	1904
Nainital	646	3912
UdhamSingh Nagar	254	1504

Table A1. Comparison between forest fire incidents reported by MODIS and VIIRS sensors for the year 2021 in 13 districts of Uttarakhand

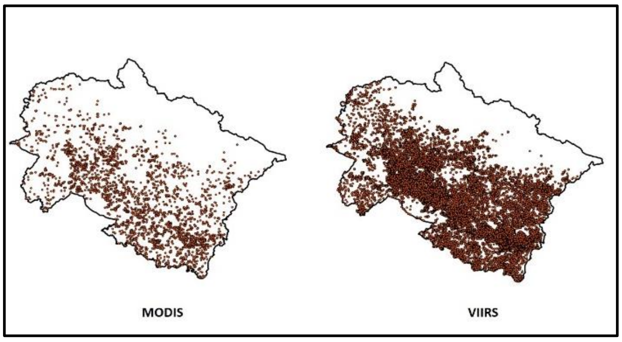

Figure A1. Representation of locations of fire hotspots captured by MODIS and VIIRS sensors in Uttarakhand for year 2021 (Data source: FIRMS portal of NASA)

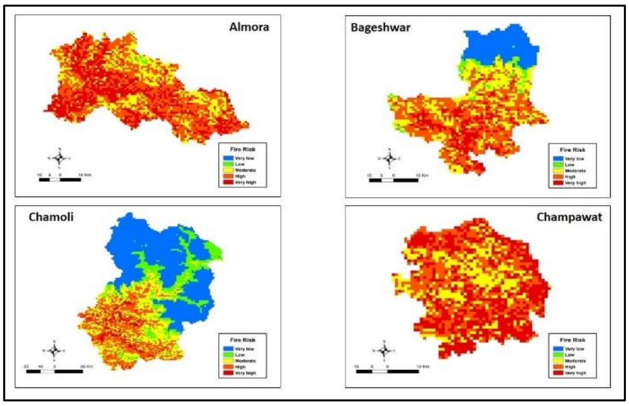

Figure A2. Forest Fire Risk Maps for districts of Almora, Bageshwar, Chamoli & Champawat

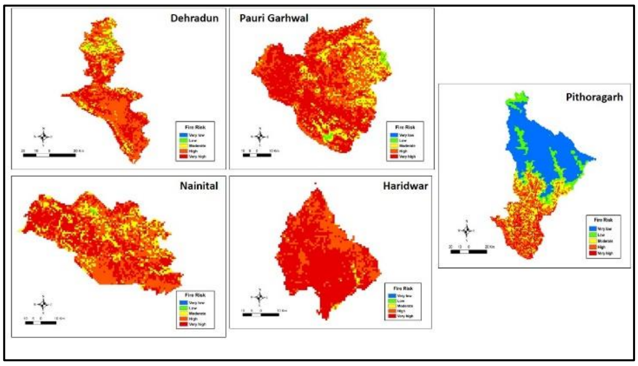

Figure A3. Forest Fire Risk Maps for districts of Dehradun, Pauri Garhwal, Nainital, Haridwar, Pithoragarh

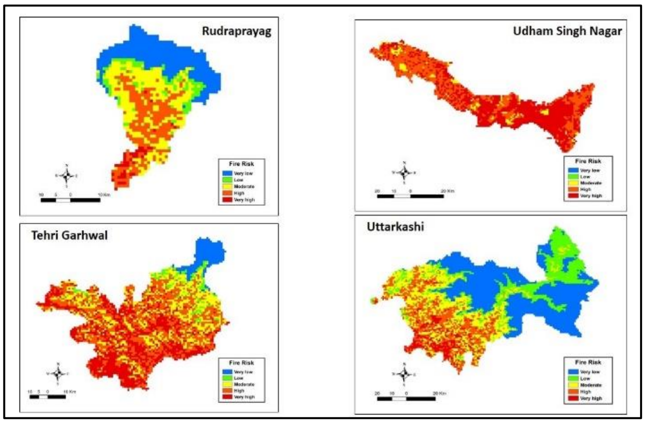

Figure A4. Forest Fire Risk Maps for districts of Rudraprayag, Udham Singh Nagar & Uttarkashi