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Forest Fire Risk Assessment using Fuzzy Analytic Hierarchy Process

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Abstract

The goal of present investigation was to generate forest fire risk zones in Solan district of Himachal Pradesh. The methodology applied was based on Fuzzy Analytic Hierarchy Process (FAHP) technique which involved socio-economic and bio-physical factors for risk assessment. Risk factors were selected on the bases of occurrence of forest fire in the area during past few years. Results revealed highest weight for fuel type (0.3109) followed by aspect (0.2487), agricultural workers (0.1341), nutritional density (0.1244), population density (0.0622), slope (0.0524),elevation (0.0311), literacy rate (0.0207) and distance from road (0.0155), respectively. Out of total geographical area, 4.15% area was classified under very high risk, while 40.63% and 54.00% area was under high and moderate risk, respectively. Area under low risk (0.84%) and very low risk (0.37%) were extremely less. The results were in agreement with actual fire occurrences in the area.

Article History

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Keywords

Cumulative Fire Risk Index;
FAHP;
Forests Fire;
Index modeling;
MCDA;
Risk assessment.

Introduction

Forest fires are extensive and critical facet of the world. The annual global area burned due to forest fire ranges from 300 and 450 Mha.[1] Over 80 percent of the global area burned occurs in grasslands and savannahs, primarily in South Asia, Africa, Australia and South America. Globally fires are frequent over most of the earth except in areas of scant vegetation and near the poles.[2]

India witnesses most of severe forest fires during the summer season in the hills of Himachal Pradesh.[3]

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Forest fires have caused extensive damage in recent years leading to loss of wildlife habitat and biodiversity, change in micro-climate, adverse effect on livelihood of people, addition of green-house gases etc. Average estimated loss due to forest fire in Himachal Pradesh is INR 113 million per annum.[4] The forests of Himachal Pradesh are mainly comprised of Chir, Oak, Deodara, Khair, Saal, Bamboo and other broad-leaved tree species. Out of above species area occupied by Chir is highly prone to forest fires due to shedding of highly inflammable chir needles.[5] The forests of the Solan district are occupied by pure and mixed stands of chir pine and mostly conform to lower Shiwalik chir pine ($9C_1a$) forest type and covers 7.68 per cent of total area of district.[5-6] There was need to generate forest fire risk zone for the study area in order to carry out prevention and management measures.

Common practice of Forest Fire Risk Zones has been delineated by assigning knowledge base weights to the risk factor classes according to their sensitivity to fire. Fuzzy Analytic Hierarchy Process (FAHP) has been used as multi-criteria decision analysis (MCDA) tool for weight estimation.[7-9]

Study Area

The study was carried out in Solan district of Himachal Pradesh, India. Solan occupied 10 percent area of the state i.e. 1,93,600 hectares. The area was primarily occupied by Pinus roxburghii, Quercus leucotric hophora, Acacia catechu, bamboos and other broad leaved tree species. Average daily mean temperature, relative humidity and annual rainfall were 18.4 °C, 1038.2 mm and 51.2 %, respectively.

Materials and Methods

In this investigation Saaty's (1998)[7] Fuzzy Analytic Hierarchy Process (FAHP) was used. FAHP is Multi-criteria Decision Making methodology which involves decision-making framework to rank and prioritize the forest fire risk factors. Table 1 summarizes the related work done over the world.

Hierarchical Structure Development of Fire Risk Criteria

We used population density (PD), agricultural workers (AGRI-W), literacy rate (LR) nutritional density (ND), distance from road (DR), fuel type (FT), aspect (A), slope (S) and elevation (E) for evaluating the fire risk in the study area (Fig. 2).Fuzzy Analytic Hierarchy model was followed in order to construct the hierarchical structure, for reckoning fire risk (Fig. 2).

Relevant socio-economic data for sub-districts of Solan were collected from District Census Handbook. Road maps, Terrain maps and fuel type maps were generated using Shuttle RADAR Topographic Mission (90m), GLOBE COVER (300m) and GLCF, respectively.

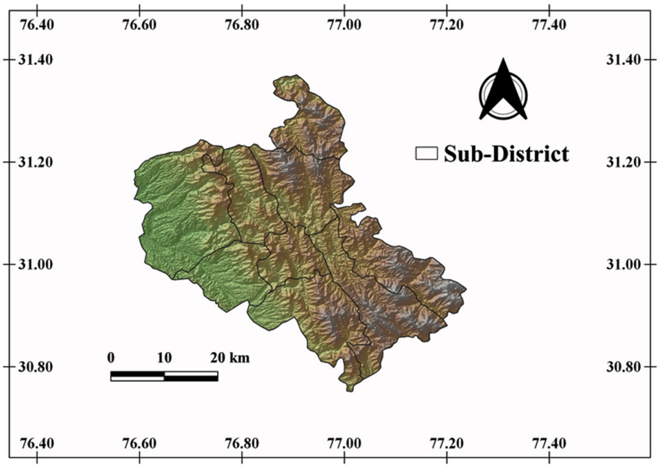

Fig. 1

Table 1. Summary of Related Works

First Author	Year	Place of Study	Title of Research Work	Variable Studied and Fire Risk Model
Aumedes[10]	2017	Global	Human-caused fire occurrence modelling in perspective: a review	Distance from roads, railways, urban areas and settlements Model: HCF model (Human Caused Fire)
Ruffault[11]	2017	France	Contribution of human and biophysical factors to the spatial distribution of forest fire ignitions and large wildfires in a French Mediterranean region	
Ajin[12]	2016	Kerala, India	Forest Fire Risk Zone Mapping Using RS and GIS Techniques: A Study in Achankovil Forest Division, Kerala, India.	Distance from roads and distance from settlements Model: FRI (Fire Risk Index)
Baweja[13]	2014	Himachal Pradesh, India	Perceptions of communities exposed to forest fires in western Himalayan region of India.	Family size and literacy rate
Vilar[14]	2014	Europe	Modelling socio-economic drivers of forest fires in the Mediterranean Europe.	Population density, road networks, wildland-urban interface, railway network, protected area, landscape fragmentation etc. Model: Logistic Regression Model
Spies[15]	2014	Oregon	Examining fire-prone forest land -scapes as coupled human and natural systems	Ownership of land
Ganteaume[16]	2013	Europe	A review of the main driving factors of forest fire ignition over Europe.	Unemployment rate, transport networks and distance to urban areas
Lafragueta[17]	2013	Spain	GIS and MCE-based forest fire assessment and mapping- A case study in Huesca, Aragon, Spain.	Distance from roads, railway track, camping and settlements Model: FRI (Fire Risk Index)
Sharma[18]	2012	Himachal Pradesh, India	Fuzzy AHP for forest fire risk modeling	Distance from road and distance from settlement Model: CFRISK (Cumulative Fire Risk Index)
Gai[19]	2011	China	GIS-based Forest Fire Risk Assessment and Mapping	Population density and value of forest resources Model: FRI (Fire Risk Index)
Hoyo[20]	2011	Spain	Logistic regression models for human-caused wildfire risk estimation: analysing the effect of the spatial accuracy in fire occurrence data	Road infrastructure, recreational and natural protected areas, Cattle-grazing pressure, Buffer of electric lines etc. Model: Logistic Regression Models
Archibald[21]	2010	South Africa	Southern African fire regimes as revealed by remote sensing	Population density Model: FRP (Fire Radiative Power Index)

...Contd

First Author	Year	Place of Study	Title of Research Work	Variable Studied and Fire Risk Model
Calcerrada[22]	2010	Spain	Spatial modelling of socioeconomic data to understand patterns of human-caused wildfire ignition risk in the SW of Madrid (central Spain)	Population, secondary housing, cattle, sheep and goats
Vadrevu[23]	2010	Andhra Pradesh, India	Fire Risk Evaluation using multi-criteria analysis- A case study	Population density, agri-cultural workers, nutritional density and literacy rate Model: Analytical Hierarchy Process (AHP)
Leone[24]	2009	Mediterranean region	Human factors of fire occurrence in the Mediterranean	Agricultural burning, bonfires, power line, engines, machines etc.
Martinez[25]	2008	Spain	Human-caused wildfire risk rating for prevention planning in Spain	Rural exodus, forest lands, rural population aging or declining fuel accumulation in abandoned agricultural lands, lack of interest in conservation etc. Model: Logistic Regression Model
Maingi[26]	2007	United States of America	Factors influencing wildfire occurrence and distribution in eastern Kentucky, USA	Unemployment rates, distance to roads and distance to populated places.
Yang[27]	2007	United States	Spatial Patterns of Modern Period Human-Caused Fire Occurrence in the Missouri Ozark Highlands	Roads, municipalities, ownership, and population density
Rawat[28]	2003	Uttarakhand, India	Fire Risk Assessment for Forest Fire Control Management in Chilla Forest Range of Rajaji National Park, Uttaranchal, India	Road index and settlement index Model: CFRISK (Cumulative Fire Risk Index)

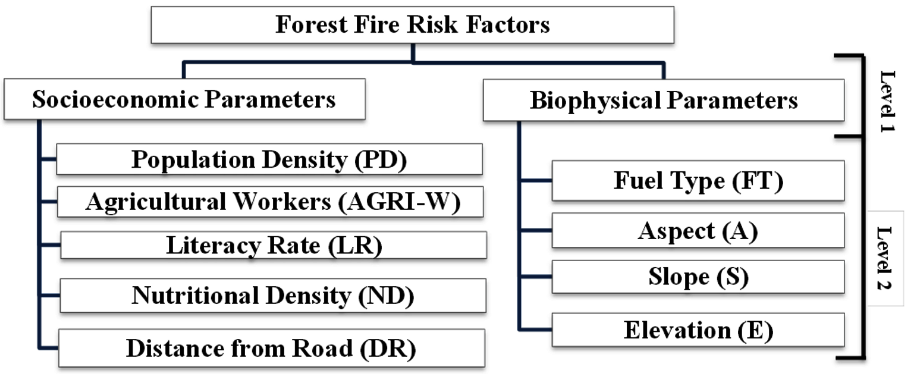

Fig. 2: Hierarchial Data Organization for Quantifying Fire Risk in the Study Area

Table 2: Index Value and Fire Rating Classes for Forest Fire Risk Parameters

Parameter	Class	Index Value	Fire rating class
Population Density			
(People km^{-2})	0-150	1	Very low
	150-300	2	Low
	300-450	3	Moderate
	450-600	4	High
	≥600	5	Very high
Literacy Rate			
(%)	0-20	5	Very high
	20-40	4	High
	40-60	3	Moderate
	60-80	2	Low
	80-100	1	Very low
Agricultural Workers			
(people)			
	0-5000	1	Very low
	5000-10000	2	Low
	10000-15000	3	Moderate
	15000-20000	4	High
	≥20000	5	Very high
Nutritional Density			
(People km^{-2})	0-100	1	Very low
	100-200	2	Low
	200-300	3	Moderate
	300-400	4	High
	≥400	5	Very high
Distance from Road Network			
(km)	0-1.00	5	Very high
	1.00-2.00	4	High
	2.00-3.00	3	Moderate
	3.00-4.00	2	Low
	≥ 4.00	1	Very low
Fuel Type	Conifer Forest	5	Very high
	Broad-leaved Forest	4	High
	Mixed Forest	3	Moderate
	Scrub Lands	2	Low
	Cultivated Areas	2	low
	Urban Areas	1	Very low
	Bare Areas	1	Very low

...contd

Parameter	Class	Index Value	Fire rating class
Aspect	North	1	Very low
	Northeast	1	Very low
	Northwest	2	Low
	West	2	Low
	East	3	Moderate
	Southeast	4	High
	Southwest	5	Very high
	South	5	Very high
Elevation (m)	≤500	5	Very high
	500-1000	4	High
	1000-1500	3	Moderate
	1500-2000	2	Low
	≥2000	1	Very low
Slope (degree)	0-10	1	Very low
	10-20	2	Low
	20-30	3	Moderate
	30-40	4	High
	≥40	5	Very high

Forest Fire Risk Index

All factors were classified into five classes, where higher value represented more risk as compared to the lower values (Table 2).

Fuzzy Analytic Hierarchy Process (FAHP)

FAHP was used for determining weights for the parameters. A judgmental pair wise comparison matrix 'A', was formed using the comparison scales (Table 3). Each entry a_{ij} of the matrix 'A' was formed comparing the row element a_i with the column element a_j.[29]

A = (a_{ij}) (i,j …n = 1,2…n; n= number of criteria)

The entries a_{ij} in matrix 'A' were done following rules given below:

$$a_{ij} > 0; a_{ij} = \frac{1}{a_{ji}}; a_{ii} = 1 \text{ for all i}$$

$$\mathbf{A} = \begin{bmatrix} a_{11} \cdots & a_{1j} \cdots & a_{1n} \\ \vdots & \vdots & \vdots \\ 1/a_{1j} \cdots & a_{jj} \cdots & a_{jn} \\ \vdots & \vdots & \vdots \\ 1/a_{1n} \cdots & 1/a_{jn} \cdots & a_{nn} \end{bmatrix}$$

Standardized matrix 'W' was formed by using following equation:

$$W = (w_{ij}) = \frac{a_{ij}}{\sum_{j=1}^{n} a_{ij}}$$

Final weights were derived by taking row average of matrix 'W'.

Table 3: Scale used in Fuzzy Analytical Hierarchy Process[30]

Intensity of scale	Linguistic Variable
1	Equally important
3	Weakly important
5	Essentially important
7	Very strongly important
9	Absolutely important
2,4,6,8	intermediate values between two adjacent judgments

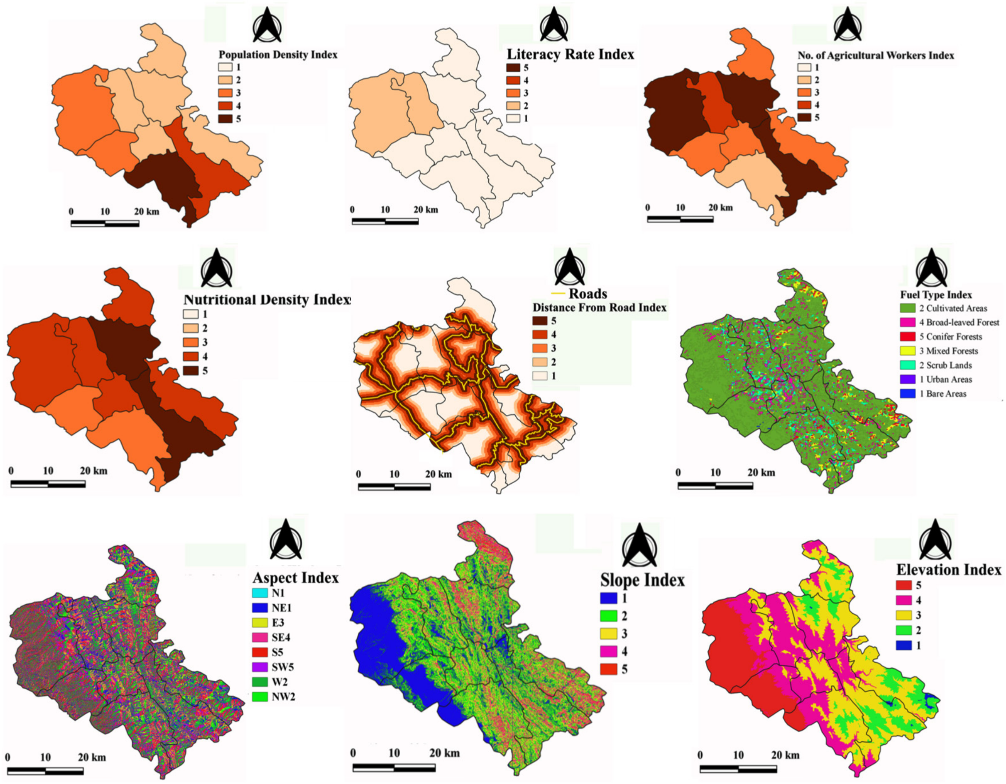

Fig. 3: Index Map for Socio-Economic and Bio-Physical Factors

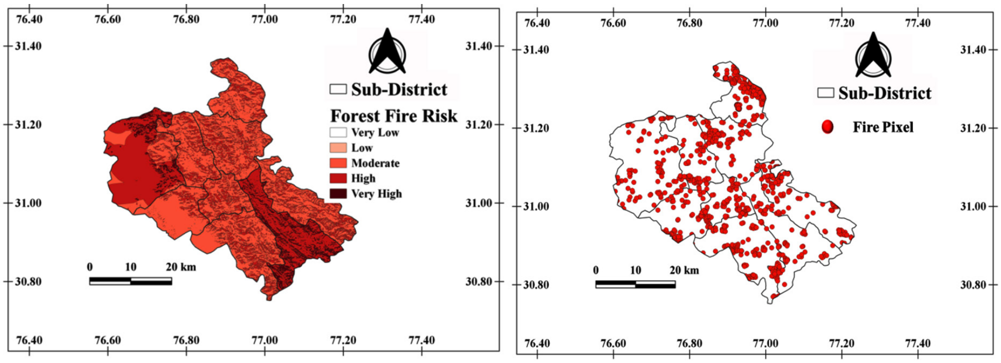

Fig. 4: (a) Forest Fire Risk Map for Solan district and (b) Forest Fire hot spot derived from NASA FIRMS datasets for the year 2018

Table 4: Estimated Weights of Forest Fire Risk Parameters

Socio-economic Parameter	Weight	Bio-physical Parameter	Weight
Population density (person km^{-2})	0.0622	Fuel type	0.3109
Literacy rate (%)	0.0207	Aspect	0.2487
Agricultural workers (person)	0.1341	Slope (degree)	0.0524
Nutritional density (person km^{-2})	0.1244	Elevation (m)	0.0311
Distance from road (m)	0.0155		

Consistency of comparisons

The value of λ_{max} was required to calculate the consistency ratio (CR).[24]

Consistency index (CI) = (λ_{max}–n) / (n-1)

Where,
λ_{max} = largest eigen value and n = number of criteria

The final consistency ratio was calculated by dividing the consistency index with the random index

$$CR = CI / RI$$

Where,
RI = Random index and CI = Consistency index

Consistency ratio was designed such a way that shows a reasonable level of consistency in the pair wise comparisons if CR < 0.10 and CR ≥ 0.10 indicated inconsistent.

Results and Discussion

Results pertaining to estimated weights of selected fire risk factors revealed highest weight for fuel type (0.3109) followed by aspect (0.2487), agricultural workers (0.1341), nutritional density (0.1244), population density (0.0622), slope (0.0524), elevation (0.0311), literacy rate (0.0207) and distance from road (0.0155), respectively (Table 4).

The resulting weights from Fuzzy Analytic Hierarchy Process were applied in the Cumulative Forest Fire Risk Index model. Table 5 demonstrated the fire risk for five classes of CFRISK index value. CFRISK model had been shown in the following equation:-

CFRISK = 0.0622*PDI +0.0207*LRI + 0.1341*AWI + 0.1244*NDI + 0.0155*DRI+ 0.3109*FTI + 0.0524*SI+ 0.2487*AI + 0.0311*EI

Where;

CFRISK =	Cumulative Fire Risk Index
PDI =	Population density index
LRI =	Literacy rate index
AWI =	Agricultural worker index
NDI =	Nutritional density index
DRI =	Distance from road index
FTI =	Fuel type index
SI =	Slope index
AI =	Aspect index
EI =	Elevation Index

Out of total geographical area of Solan district, 4.15% area was classified under very high risk, 40.63% area under high risk, 54.00% area under moderate risk, 0.84% area under low risk and 0.37% under very low risk (Fig. 4a).Accuracy of the Forest Fire Risk map was tested using NASA FIRMS forest fire dataset for the year 2018 (Fig. 4b). The Forest Fire Risk map for the three classes alone *viz.* moderate, high and very high predicted 99.4% of the total fire pixels (1012).The moderate class predictive capability was highest (60.77%), followed by high (33.99%) and very high (4.64%) fire risk class.

Table 5: Cumulative Forest Fire Risk (CFRISK) Index potential scale[24]

Index	Forest Fire Risk
0-1	Very low
1-2	Low
2-3	Moderate
3-4	High
4-5	Very high

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