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.

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
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 greenhouse gases etc. Average estimated loss due to forest fire in Himachal Pradesh is INR 113 million per annum. The forests of Himachal Pradesh are mainly comprised of Chir, Oak, Deodara, Khair, Saal, Bamboo and other broad-leaved tree species. Of above species area occupied by Chir is highly prone to forest fires due to shedding of highly inflammable chir needles. The forests of the Solan district are occupied by pure and mixed stands of chir pine and mostly conform to lower Shiwalik chir pine (9C1a) forest type and covers 7.68 per cent of total area of district. There was need to generate forest fire risk zone for the study area in order to carry out prevention and management measures.

Materials and Methods
In this investigation Saaty’s (1998) 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.

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 leucotrichophora, 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.

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      | 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     | 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         | 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       | 2014 | Himachal Pradesh, India | Perceptions of communities exposed to forest fires in western Himalayan region of India. | Family size and literacy rate |
| Vilar        | 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        | 2014 | Oregon         | Examining fire-prone forest land-escapes as coupled human and natural systems | Ownership of land |
| Ganteaume    | 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   | 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       | 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          | 2011 | China          | GIS-based Forest Fire Risk Assessment and Mapping | Population density and value of forest resources Model: FRI (Fire Risk Index) |
| Hoyo         | 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    | 2010 | South Africa   | Southern African fire regimes as revealed by remote sensing | Population density Model: FRP (Fire Radiative Power Index) |

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| First Author  | Year | Place of Study | Title of Research Work                                                                                                                                                                                                 | Variable Studied and Fire Risk Model                                                                 |
|--------------|------|----------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------|
| Calcerrada   | 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      | 2010 | Andhra Pradesh, India | Fire Risk Evaluation using multi-criteria analysis- A case study                                                                                                                                                    | Population density, agricultural workers, nutritional density and literacy rate Model: Analytical Hierarchy Process (AHP) |
| Leone        | 2009 | Mediterranean region | Human factors of fire occurrence in the Mediterranean                                                                                                                                                            | Agricultural burning, bonfires, power line, engines, machines etc.                                   |
| Martinez     | 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       | 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         | 2007 | United States   | Spatial Patterns of Modern Period Human-Caused Fire Occurrence in the Missouri Ozark Highlands                                                                                                                    | Roads, municipalities, ownership, and population density                                               |
| Rawat        | 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               | 0-150       | 1           | Very low          |
| (People km\(^2\))                | 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             | 0-5000      | 1           | Very low          |
| (people)                         | 5000-10000  | 2           | Low               |
|                                  | 10000-15000 | 3           | Moderate          |
|                                  | 15000-20000 | 4           | High              |
|                                  | ≥20000      | 5           | Very high         |
| Nutritional Density              | 0-100       | 1           | Very low          |
| (People km\(^2\))                | 100-200     | 2           | Low               |
|                                  | 200-300     | 3           | Moderate          |
|                                  | 300-400     | 4           | High              |
|                                  | ≥400        | 5           | Very high         |
| Distance from Road Network       | 0-1.00      | 5           | Very high         |
| (km)                             | 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
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 $a_j$.

$A = (a_{ij}) (i,j \ldots n = 1,2 \ldots n; n=\text{number of criteria})$

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

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

$$A = \begin{bmatrix}
    a_{11} & \ldots & a_{1i} & \ldots & a_{1n} \\
    \vdots & \ddots & \vdots & \ddots & \vdots \\
    1/a_{ij} & \ddots & a_{ij} & \ddots & a_{jn} \\
    \vdots & \ddots & \vdots & \ddots & \vdots \\
    1/a_{in} & \ldots & 1/a_{jn} & \ldots & a_{nn}
\end{bmatrix}$$

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’.

| 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) |  |  |  |
|------|------|------|------|
| $\leq500$ | 5 | Very high |
| 500-1000 | 4 | High |
| 1000-1500 | 3 | Moderate |
| 1500-2000 | 2 | Low |
| $\geq2000$ | 1 | Very low |

| Slope (degree) |  |  |  |
|----|----|----|----|
| 0-10 | 1 | Very low |
| 10-20 | 2 | Low |
| 20-30 | 3 | Moderate |
| 30-40 | 4 | High |
| $\geq40$ | 5 | Very high |

Table 3: Scale used in Fuzzy Analytical Hierarchy Process

| 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 \(\lambda_{\text{max}}\) was required to calculate the consistency ratio (CR).\(^{24}\)

Consistency index (CI) = \(\frac{\lambda_{\text{max}}-n}{n-1}\)

Where,
\(\lambda_{\text{max}}\) = largest eigen value and \(n\) = number of criteria

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

\[
\text{CR} = \frac{\text{CI}}{\text{RI}}
\]

Where,
\(\text{RI}\) = Random index and \(\text{CI}\) = Consistency index

Consistency ratio was designed such a way that shows a reasonable level of consistency in the pair wise comparisons if \(\text{CR} < 0.10\) and \(\text{CR} \geq 0.10\) 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:

\[
\text{CFRISK} = 0.0622 \times \text{PDI} + 0.0207 \times \text{LRI} + 0.1341 \times \text{AWI} + 0.1244 \times \text{NDI} + 0.0155 \times \text{DRI} + 0.3109 \times \text{FTI} + 0.0524 \times \text{SI} + 0.2487 \times \text{AI} + 0.0311 \times \text{EI}
\]

Where;
\(\text{CFRISK}\) = Cumulative Fire Risk Index

\(\text{PDI}\) = Population density index

\(\text{LRI}\) = Literacy rate index

\(\text{AWI}\) = Agricultural worker index

\(\text{NDI}\) = Nutritional density index

\(\text{DRI}\) = Distance from road index

\(\text{FTI}\) = Fuel type index

\(\text{SI}\) = Slope index

\(\text{AI}\) = Aspect index

\(\text{EI}\) = 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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