Study on the Wildfires Occurring Risk Based on Fuzzy FTA

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Abstract. The serious consequences of wildfire urges scholars to pay more attention to control the occurrence of wildfire. Wildfire occurring is considered to be the result of satisfying comprehensive conditions including sufficient forest fuel, high forest fire-danger weather ratings and ignition source in this paper. In order to further study the causes and potential risks of wildfires. An assessment algorithm used for wildfires occurring risk is proposed by combining trapezoidal fuzzy theory and FTA. Furthermore, Xiangxi was chosen as application example, and the result shows that the top five dangerous BEs are ‘High average temperatures (X1)’, ‘illegal sacrifices (burning) (X23)’, ‘large underground humics (X7)’, ‘large weeds and dwarf shrubs (X11)’, ‘luxuriant tree branches (X14)’ exist highly risk. Finally, based on the evaluation results, suggestions are provided for the above basic events with greater risks.

1. Introduction
Wildfires have been a common occurrence since the appearance of forests on earth. On average, more than 200,000 wildfires occur every year in the world, accounting for more than 1‰ of the total forest area of the world. China has an average of more than 10,000 wildfires every year, burning hundreds of thousands to millions of hectares of forest, accounting for 5-8 per thousand of the country's forest area. These accidents will seriously affect the normal life of the residents and cause an enormous economic cost [1-4].

Many researches have been done about the adverse effects of wildfires. The coupling effect of vegetation, topography, surface availability, season, region and other factors on the severity and the occurrence probability of wildfires is considered from the aspect of natural factors and human factors [5; 6]. Furthermore, many research methods are adopted to evaluate the hazards of wildfires, such as logistic regression model [6], cellular automata theory [7], dynamic heat balance equation [8], artificial neural network [9], spectral analysis [10] et al. In addition, related prediction algorithms and methods of wildfires are taken into consideration. Michael C. et al [11] proposed a prediction method for wildfires in south-central America based on the downscaled climate projections and physical chemistry fire frequency algorithm (PC2FM). Zhang H. et al [12] established the binary logistic regression model to study the probability of occurrence on wildfires in Northeast China. Although
some achievements have been made in this field, the prediction and prevention of wildfires still needs to be further improved due to complex properties of coupled multi-factors on wildfires [13].

Unlike the perspectives of previous research, wildfire occurring is considered to be the result of satisfying comprehensive conditions including sufficient forest fuel, high forest fire-danger weather ratings and ignition source. Furthermore, the risk assessment algorithm consisting above factors is established by using the fuzzy FTA in the paper. Finally, the potential risks are found and the safety suggestions are put forward.

2. The assessment algorithm of wildfire occurring

2.1. Establishing fault tree

Wildfires occurring is regarded as the top event (TE) in the fault tree. Wildfires will happen easily in case of sufficient forest fuel [14], high forest fire-danger weather ratings [15] and ignition source [16]. Therefore, these three factors are considered as intermediate events in the fault tree, then various factors associated with above events is further analyzed. Wildfires occurring fault tree is shown in Fig. 1 and Table 1 presents the meanings of basic events (BEs).

![Wildfires occurring fault tree](image)

**Table 1** Meanings of BEs in the wildfires occurring fault tree.

| Symbol | Meaning | Symbol | Meaning |
|--------|---------|--------|---------|
| $T_1$  | Wildfires occurring | $X_9$  | Dense underground tree roots |
| $M_1$  | Sufficient forest fuel | $X_{10}$ | Large forest surface litter |
| $M_2$  | High forest fire-danger weather ratings | $X_{11}$ | Large weeds and dwarf shrubs |
| $M_3$  | Ignition source | $X_{12}$ | Large fallen trees and tree stump |
| $M_4$  | Sufficient underground fuel | $X_{13}$ | Large lichens and mosses |
| $M_5$  | Sufficient surface fuel | $X_{14}$ | Luxuriant tree branches |
| $M_6$  | Sufficient forest fuel | $X_{15}$ | Large dead wood |
| $M_7$  | Natural fire | $X_{16}$ | Higher thunderstorm frequency |
| $M_8$  | Artificial fire | $X_{17}$ | Spontaneous combustion of peat |
| $X_1$  | High average temperatures | $X_{18}$ | Plant combustion |
| $X_2$  | Low relative humidity | $X_{19}$ | Volcanic explosion |
| $X_3$  | High gale weather frequency | $X_{20}$ | Discarded cigarette butts |
| $X_4$  | Low average precipitation | $X_{21}$ | Illegal picnic |
| $X_5$  | Low forest fuel moisture | $X_{22}$ | Illegal moorburn |
| $X_6$  | Severe persistent drought | $X_{23}$ | Illegal sacrifices (burning) |
| $X_7$  | Large underground humics | $X_{24}$ | Lawbreakers setting fire |
| $X_8$  | Abundant underground peat |

Based on the established fault tree above, the minimal cut sets are shown below:

$K_1=\{X_1, X_{10}, X_{15}\}$; $K_2=\{X_1, X_{11}, X_{17}\}$; $K_3=\{X_1, X_{11}, X_{14}\}$; $K_4=\{X_1, X_{10}, X_{19}\}$;

...
\( K_{48} = \{ x_1, x_2, x_3, x_4 \} \); \( K_{48} = \{ x_5, x_6, x_7 \} \);

And the minimal path sets are as follows:

\( P_1 = \{ x_1, x_2, x_3, x_4, x_6, x_8 \} \); \( P_2 = \{ x_1, x_4, x_9, x_{10}, x_{11}, x_{12}, x_{13}, x_{14}, x_{15} \} \); 

\( P_3 = \{ x_{16}, x_{17}, x_{18}, x_{19}, x_{20}, x_{21}, x_{22}, x_{23}, x_{24} \} \).

There are 486 minimum cut sets and 3 minimum path sets in the fault tree. The minimum cut sets indicate the number of paths for wildfires occurring and wildfires will happen when one of the paths links. In addition, the minimum path sets represents the means of avoiding wildfires occurring. Therefore, the minimum path sets are selected to calculate the probability of the TE by comparing the numbers of the two sets.

2.2. The calculation process of fuzzy fault tree

2.2.1. Expert evaluation. Each expert often evaluates BEs according to the previous work experience and common sense, so there would be errors. Therefore, three experts in related fields are invited to evaluate the probabilities of fuzzy events for the more accurate assessment, and weights for each experts are determined according to Table 2. Table 3 presents the weights of different information indicators of each experts, which shows the weights of three experts are 0.438, 0.344 and 0.218, respectively. In addition, the common fuzzy evaluation language consists of very low (VL: 0.0, 0.0, 0.1, 0.2), low (L: 0.1, 0.2, 0.2, 0.3), mildly low (ML: 0.2, 0.3, 0.4, 0.5), medium (M: 0.4, 0.5, 0.5, 0.6), mildly high (MH: 0.5, 0.6, 0.7, 0.8), high (H: 0.7, 0.8, 0.8, 0.9) and very high (VH: 0.8, 0.9, 1.0, 1.0).

Table 2 Weights of different information indicators.

| Constitution       | Classification | Score | Constitution       | Classification | Score |
|--------------------|----------------|-------|--------------------|----------------|-------|
| Professional position |                |       | Education level    |                |       |
| Professor          |                | 5     | ≥20                |                | 5     |
| Associate professor |                | 4     | 5                  |                | 5     |
| Engineer           |                | 3     | 15–20              |                | 4     |
| Technician         |                | 2     | 6–9                |                | 3     |
| Worker             |                | 1     | Service time       | 10–15          | 3     |
| PhD                |                | 5     |                    |                |       |
| Master             |                | 4     | 6–9                |                | 2     |
| Bachelor           |                | 3     | ≤5                 |                | 1     |
| Junior college     |                | 2     |                    |                |       |
| School             |                | 1     |                    |                |       |

Table 3 Expert weighting.

| No. of expert | Professional position | Service time (Years) | Education level | Score | Weights |
|---------------|-----------------------|----------------------|-----------------|-------|---------|
| 1             | Professor=5           | 15-20=4              | PhD=5           | 5+5+4=14 | 0.438   |
| 2             | Associate Professor=4 | 6–9=2                | PhD=5           | 5+4+2=11 | 0.344   |
| 3             | Technician=2          | 5≤=1                 | Master=4        | 4+2+1=7  | 0.218   |
| Total         | -                     | -                    | -               | 32     | 1       |

2.2.2. Aggregating stage. Experts may have different cognitions of each evaluation object. Therefore, it is necessary to aggregate the opinions until a consensus reached. The specific algorithm is described as follows:

(1) Calculating the degree of agreement \( (DA) \) of each pair of experts

\( A = (a_1, a_2, a_3, a_4) \) and \( B = (b_1, b_2, b_3, b_4) \) are supposed as standard trapezoidal fuzzy numbers. The \( DA \) function is defined as follows:
\[ DA(A, B) = 1 - \frac{1}{4} \sum_{i=1}^{4} |a_i - b_i| \]  
(1)

Where \( DA(A, B) \in [0, 1] \), and the larger \( DA(A, B) \) represents the stronger similarity of fuzzy number \( A \) and \( B \), which means that the agreement degree of two expert’s opinion is higher.

(2) Calculating the average of agreement (\( AA \)) of each expert

\[ AA(E_i) = \frac{1}{n-1} \sum_{j=1}^{n} DA_i(A_j, A_j) \]  
(2)

Where \( n \) is the sum of experts, and \( AA(E_i) \) indicates the average agreement degree between an expert and all experts opinion.

(3) Calculating the relative of agreement (\( RA \)) of each expert

\[ RA(E_i) = \frac{AA(E_i)}{\sum_{i=1}^{n} AA(E_i)} \]  
(3)

Where \( RA(E_i) \) is the weight of the average agreement degree for the opinion of an expert.

(4) Estimating the consensus coefficient (\( CC \)) degree of each expert

\[ CC(E_i) = \beta \cdot W(E_i) + (1 - \beta) \cdot RA(E_i) \]  
(4)

Here, \( \beta \) is relaxation factor and \( \beta \in (0, 1) \). When \( \beta = 0 \), the opinion of this expert is considered no importance. When \( \beta = 1 \), the consensus of this expert is equal to its weight. The consensus coefficient (\( CC \)) degree provides a good measurement to evaluate the related importance degree of each expert’s opinion. We set \( \beta = 0.5 \) in this paper.

(5) Finally, the aggregated results of expert judgment \( R_{AG} \) can be obtained as follows:

\[ R_{AG} = \sum_{i=1}^{n} CC(E_i) \cdot R_i \]  
(5)

Here, \( R_{AG} \) is the fuzzy number of BEs after aggregating, and \( R_i \) is the trapezoid fuzzy probability given by an expert.

2.2.3. Defuzzification process. In order to make the results more accurate, the fuzzy probability of TE needs to be defuzzified, which is shown as follows:

\[ P_{TE} = \frac{1}{3} \left( a_1 + a_2 \right)^2 - a_1 a_2 - (a_2 + a_1)^2 + a_1 a_2 \]

\[ = \frac{1}{3} \left( a_2 + a_1 \right)^2 - a_2 a_1 - (a_2 + a_1)^2 + a_2 a_1 \]  
(6)

2.2.4. Transforming failure possibility (FP) of BEs into actual failure probability (AFP). In the fuzzy FTA method, the possibility of each BE is represented by a fuzzy number, which is called the failure
possibility (FP). There is inconsistency between AFP of a certain BE and FP of each vague event, which should be lowered. Hence, the AFP is derived from FP of a certain BE and the equation are presented below:

\[
AFP = \begin{cases} 
\frac{1}{10^n} & FP \neq 0 \\
0 & FP = 0 
\end{cases}
\] (7)

2.2.5. Analysis for importance degree of BEs. The importance degree of each basic event is related to the occurrence probability of the TE. Eq. (8) determines the calculation process.

\[
I_x = \frac{P_{TE} - P_{TE|I_x=0}}{P_{TE}}
\] (8)

Where \(I_x\) is the importance degree of a BE; and \(P_{TE|I_x=0}\) is the probability of TE when the occurrence probability of specific BE is zero.

3. An illustrative case for the assessment algorithm of wildfire

Located in the south of the Yangtze River, Xiangxi has a low dimension and is a subtropical monsoon humid climate with obvious continental characteristics which leads to a high forest coverage up to 70.24%. In addition, this area mainly including 11 ethnic minorities such as Tujia, Miao, Yi, Yao, Bai, and Hui, etc. has rich cultural customs.

3.1. The calculation process of fuzzy fault tree

3.1.1. Expert evaluation on the fault tree of wildfires occurring. After completing the investigation about the occurrence conditions of wildfires, three experts in related field are invited to judge BEs leading to the wildfires occurring, and their judgments are shown in Table 4.

| BEs | Expert 1 | Expert 2 | Expert 3 | BEs | Expert 1 | Expert 2 | Expert 3 |
|-----|----------|----------|----------|-----|----------|----------|----------|
| \(X_1\) | VH       | VH       | H        | \(X_{13}\) | VH   | H        | H        |
| \(X_2\) | MH       | MH       | H        | \(X_{14}\) | VH   | VH       | VH       |
| \(X_3\) | H        | H        | H        | \(X_{15}\) | MH   | MH       | H        |
| \(X_4\) | H        | H        | MH       | \(X_{16}\) | VH   | VH       | H        |
| \(X_5\) | MH       | MH       | MH       | \(X_{17}\) | H    | H        | MH       |
| \(X_6\) | H        | H        | H        | \(X_{18}\) | MH   | H        | H        |
| \(X_7\) | VH       | VH       | VH       | \(X_{19}\) | MH   | MH       | MH       |
| \(X_8\) | H        | MH       | H        | \(X_{20}\) | H    | H        | VH       |
| \(X_9\) | VH       | H        | H        | \(X_{21}\) | H    | H        | H        |
| \(X_{10}\) | MH       | H        | H        | \(X_{22}\) | H    | VH       | H        |
| \(X_{11}\) | VH       | VH       | VH       | \(X_{23}\) | VH   | VH       | VH       |
| \(X_{12}\) | H        | MH       | MH       | \(X_{24}\) | H    | H        | VH       |

3.1.2. Aggregate calculation of expert opinions. According to the algorithm of fuzzy fault tree mentioned in section 2.3, aggregating stage of the basic event \(X_1\) in the fire occurring fault tree is conducted, which includes the calculations such as degree of agreement (DA), average agreement
degree (AA), relative agreement degree (RA), etc. The aggregating calculation process of basic events $X_1$ is shown in Table 5 and the calculations for other BEs are the same, so they are omitted.

### Table 5: Aggregating calculation of basic events $X_1$.

|   | VH (0.8,0.9,1.0,1.0) | RA(E1) | DA_{12} | 1.0000 |
|---|---------------------|--------|---------|--------|
| A1 |                     | 0.3409 |         |        |
| A2 |                     | 0.3409 |         | 0.8750 |
| A3 | $H \ (0.7,0.8,0.8,0.9)$ | 0.3182 |         | 0.8750 |

$AA(E1) = 0.9375$, $W(E1) = 0.438$, $CC(E1) = 0.3895$

$AA(E2) = 0.9375$, $W(E2) = 0.344$, $CC(E2) = 0.3425$

$AA(E3) = 0.8750$, $W(E3) = 0.218$, $CC(E3) = 0.2681$

$R_{AG} = CC(E1) \times R_1 + CC(E2) \times R_2 + CC(E3) \times R_3 = (0.7732, 0.8732, 0.9464, 0.9732)$

#### 3.1.3. Calculating the probability of the wildfires occurring.

Due to the numbers of minimum cut sets are too numerous, the minimum path sets are used to calculate the probability of TE in the wildfires occurring fault tree. Eq. (9) shows the calculation of the TE.

$$Q = [1 - (1-q_1) \times L \times (1-q_6)] \times [1 - (1-q_7) \times L \times (1-q_{15})] \times [1 - (1-q_{16}) \times L \times (1-q_{21})]$$

(9)

According to the calculation results, the probability of wildfire occurring (IE) is 2.570%, which indicates that potential risks exist.

#### 3.2. Analysis for importance degree of BEs

The importance degree of BEs is determined by eq. (9), and the importance degree of all BEs in wildfire occurring is calculated and sorted. Through sequencing, the key factors affecting the wildfire occurring are discovered. The result is presented in Table 7.

### Table 6: Converting failure possibility (FP) into actual failure probability (AFP).

| BEs | Aggregate results of BEs | Defuzzification of Bes (FP) | AFP |
|-----|--------------------------|-----------------------------|-----|
| $X_1$ | (0.7372, 0.8732, 0.9464, 0.9732) | 0.8887 | 0.0706 |
| $X_2$ | (0.6251, 0.7251, 0.7628, 0.8628) | 0.7439 | 0.0244 |
| $X_3$ | (0.7000, 0.8000, 0.8000, 0.9000) | 0.8000 | 0.0355 |
| $X_4$ | (0.6470, 0.7470, 0.7737, 0.8738) | 0.7604 | 0.0272 |
| $X_5$ | (0.5002, 0.6003, 0.7003, 0.8004) | 0.6503 | 0.0135 |
| $X_6$ | (0.7000, 0.8000, 0.8000, 0.9000) | 0.8000 | 0.0355 |
| $X_7$ | (0.8004, 0.9005, 1.0005, 1.0005) | 0.9227 | 0.0984 |
| $X_8$ | (0.6345, 0.7345, 0.7675, 0.8675) | 0.7510 | 0.0255 |
| $X_9$ | (0.7382, 0.8382, 0.8760, 0.9383) | 0.8455 | 0.0495 |
| $X_{10}$ | (0.7372, 0.8732, 0.9464, 0.9732) | 0.8887 | 0.0706 |
| $X_{11}$ | (0.6251, 0.7251, 0.7628, 0.8628) | 0.7439 | 0.0244 |
| $X_{12}$ | (0.8004, 0.9005, 1.0005, 1.0005) | 0.9227 | 0.0984 |
| $X_{13}$ | (0.5755, 0.6756, 0.7380, 0.8380) | 0.7068 | 0.0192 |
| $X_{14}$ | (0.7382, 0.8382, 0.8760, 0.9383) | 0.8455 | 0.0495 |
| $X_{15}$ | (0.8004, 0.9005, 1.0005, 1.0005) | 0.9227 | 0.0984 |
| $X_{16}$ | (0.5536, 0.6537, 0.7270, 0.8271) | 0.6904 | 0.0173 |
| $X_{17}$ | (0.7382, 0.8382, 0.8760, 0.9383) | 0.8455 | 0.0495 |
| $X_{18}$ | (0.8004, 0.9005, 1.0005, 1.0005) | 0.9227 | 0.0984 |
| $X_{19}$ | (0.7272, 0.8273, 0.8541, 0.9273) | 0.8323 | 0.0448 |
| $X_{20}$ | (0.7000, 0.8000, 0.8000, 0.9000) | 0.8000 | 0.0355 |
| $X_{21}$ | (0.7331, 0.8331, 0.8662, 0.9331) | 0.8394 | 0.0474 |
| $X_{22}$ | (0.8004, 0.9005, 1.0005, 1.0005) | 0.9227 | 0.0984 |
| $X_{23}$ | (0.7272, 0.8273, 0.8541, 0.9273) | 0.8323 | 0.0448 |
Table 7 Important degree and ranking of all BEs in wildfires occurring fault tree.

| BEs | Importance degree | Ranking | BEs | Importance degree | Ranking | BEs | Importance degree | Ranking |
|-----|-------------------|---------|-----|-------------------|---------|-----|-------------------|---------|
| X₁  | 0.3227            | 1       | X₉  | 0.0803            | 14      | X₁₇ | 0.0537            | 18      |
| X₂  | 0.1063            | 10      | X₁₀ | 0.0386            | 21      | X₁₈ | 0.0480            | 19      |
| X₃  | 0.1564            | 6       | X₁₁ | 0.1684            | 4       | X₁₉ | 0.0263            | 24      |
| X₄  | 0.1188            | 9       | X₁₂ | 0.0302            | 22      | X₂₀ | 0.0901            | 12      |
| X₅  | 0.0581            | 17      | X₁₃ | 0.0803            | 15      | X₂₁ | 0.0707            | 16      |
| X₆  | 0.1564            | 7       | X₁₄ | 0.1684            | 5       | X₂₂ | 0.0956            | 11      |
| X₇  | 0.1684            | 3       | X₁₅ | 0.0272            | 23      | X₂₃ | 0.2097            | 2       |
| X₈  | 0.0404            | 20      | X₁₆ | 0.1459            | 8       | X₂₄ | 0.0901            | 13      |

4. Conclusions
It can be concluded that the top five dangerous BEs are ‘High average temperatures (X₁)’, ‘illegal sacrifices (burning) (X₂₃)’, ‘large underground humics (X₇)’, ‘large weeds and dwarf shrubs (X₁₁)’, ‘luxuriant tree branches (X₁₄)’ from Table 7. These five BEs are the main factors leading the wildfire occurring. Located in the south of the Yangtze River, Hunan Province has a low latitude and is a subtropical monsoon humid climate with obvious continental characteristics. Thus, high average temperatures (X₁), droughts abound in summer and autumn, short cold period and long hot period are directly caused. Therefore, it is necessary to strengthen the monitor of summer and autumn in Hunan province. In addition, the characteristics of subtropical monsoon humid climate lead to the abundant rainfall. Naturally, large underground humics (X₇), large weeds and dwarf shrubs (X₁₁) and luxuriant tree branches (X₁₄) add the content of combustible matter in forest. Hence, it is imperative to remove forest fuel to reduce the possibility of wildfires.

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