Research on Fire Risk Analysis and Prevention in Wildland-Urban Interface

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Abstract. In order to enhance the capability of fire risk assessment and prevention in the Wildland-Urban Interface, and to reduce the frequency and scale of fires in these border regions, ensuring the safety of residents and their properties, this paper summarizes the research conducted by domestic and international scholars. It explains the causes of wildland-urban interface fires, considering both natural and social factors. The results indicate that wildland-urban interface fires exhibit characteristics such as abundant and continuous combustible materials, complex environments, numerous ignition points, large-scale fires, rapid spread, and difficulty in firefighting. The paper clarifies the logical analysis of fire risk in the interface areas from both regional and disaster dimensions. It establishes evaluation indicators and introduces two fire assessment methods based on topological structures. Additionally, it discusses the basis and measures for fire prevention, considering domestic and international government regulations, local standards, personnel safety evacuation, and post-fire disposal situations. The study aims to identify the shortcomings and future directions in fire risk analysis and prevention in Wildland-Urban Interface. It serves as a reference for research on fire prevention and control in these interface regions.

Keywords: Wildland-urban interface, Wildfire, Fire risk analysis, Fire prevention, topological structure.

1. Introduction

The Wildland-Urban Interface (WUI) refers to the transitional zone between forests and human-developed areas. (including buildings and other artificial structures.) Within this interface, there are rural and community residential areas, as well as places of worship, cemeteries, scenic spots, and forest parks. In recent years, rapid developments in manufacturing and logistics have made the interface a prime location for logistics and warehouse enterprises, leading to increased human activities in the area and an elevated difficulty in fire source control. This has contributed to an increased susceptibility to wildland-urban interface fires. In recent years, wildland-urban interface fires have become more frequent.

In January 2022, a forest fire occurred in Colorado, USA, spreading to nearby villages, resulting in the destruction of over 500 buildings, 2 people missing, and the evacuation of 30,000 residents. The affected area exceeded 6,200 acres. In February 2022, wildfires in Western Australia also led to the destruction of 6 houses in a village, power outages for 400 households, one person severely injured, and a burned area of nearly 4,700 hectares.

This paper summarizes the research conducted by domestic and international scholars on the risk assessment and prevention of wildland-urban interface fires. To explains the causes and characteristics of wildland-urban interface fires, clarifies the logical analysis of fire risk, and discusses the basis and measures for fire prevention. The aim is to provide reference and insights for the risk assessment and prevention of wildland-urban interface fires.

2. Causes and Characteristics of Wildland-Urban Interface Fires

In order to provide foundation for the assessment and prevention of fire risks in the WUI, this paper analyzes the origins and development of wildland-urban interface fires and elucidates the causes and characteristics by reviewing cases of wildland-urban interface fires.

2.1. Causes of WUI fires

The causes of wildland-urban interface fires are intricate [1], involving both natural and social factors. Natural factors encompass combustible material types and distribution, meteorological conditions, topography, and other elements that trigger forest fires. Similarly, natural factors such as lightning strikes and earthquakes can initiate urban fires. Social factors include the direct causes of fires in urban areas, such as residents mishandling fire or incidents involving electricity and gas, as well as indirect factors such as fire management, prevention and suppression, and the formulation and implementation of policies.

2.2. Spread of WUI fires

wildland-urban interface fires adhere to the combustion triangle [2-3], with complex conditions for propagation and spread. When spreading from forests to urban areas, the proximity of combustible materials in the interface area to buildings results in radiative heat igniting combustible materials within structures. Combustible materials in flames can easily enter indoor spaces through ventilation and smoke outlets: a gradual increase in indoor temperatures and the expansion of the fire. Conversely, when spreading from urban areas to forests, fires in buildings within the interface area can ignite accumulated tree leaves or dry branches on roofs. Improper use of outdoor sources like barbecues, bonfires, gas cylinders, and open flames for heating can also lead to fires or explosions, igniting nearby forest combustibles. Studying the spread of wildland-urban interface fires is essential for understanding the dynamic nature of fires and implementing targeted firefighting measures.

2.3. Characteristics of WUI fires

wildland-urban interface fires typically occur in economically underdeveloped regions with inadequate firefighting facilities, frequent use of fire in residents' daily lives, and a prevalence of wooden structures. Additionally, the topography is often characterized by mountains or hills, with scattered residential areas, intertwined farmland, and a complex environment. Comparative analysis of domestic and international WUI fires [4-5] reveals that high-risk areas are characterized by the continuous presence of combustible materials and a high surface combustible load [6]. Furthermore, WUI fires exhibit characteristics of both forest fires and urban fires [7], making them prone to mutual transformation. Under the influence of natural factors such as wind speed, WUI fires spread rapidly, leading to multiple ignition points, increased fire scale, and heightened firefighting challenges.

3. Risk Assessment of Wildland-Urban Interface Fires

In recent years, experts and scholars have typically used specific research areas or wildfire events as examples to employ fire risk assessment methods [8], modify wildfire dynamic simulation tools [9], and propose wildfire spread models in the interface area [10-11]. The author reviews recent literature, categorizing the assessment of fire risk in the Wildland-Urban Interface into two dimensions: regional and disaster.

3.1. Regional Dimension Fire risk Assessment

The regional dimension of fire risk assessment widely applied in forest fire contexts focuses on discussing risk factors that may lead to wildfires in a specific region or administrative area, analyzing their impact on the probability or severity of fire occurrences [12]. Using the Random Forest (RF) model to analyze fire risk in the Wildland-Urban Interface, Hou et al. [13], focusing on Anhui Province, explained the impact of nine risk factors such as population density and elevation. The results indicated that road and railway density contributed the most, contrasting with forest fires where meteorological and vegetation factors have higher contributions. Li et al. [14] compared the RF model with logistic regression in analyzing fire risk in the Yungui-Chuandian region. Both models identified the distance from roads to residential areas and human activity around roads and residential areas as the main influencing factors for fire occurrence. What’s more, the Analytic Hierarchy Process

(AHP) was applied to consider the impact of natural and social factors on fire risk in the Wildland-Urban Interface. In the natural factors category, Luo et al. [15] analyzed 11 fire risk factors of 16 major forest areas in the Wildland-Urban Interface in Guangzhou, concluding that Eucalyptus forests, pure pine forests, and Chinese fir forests have higher fire risk, while Camphor forests have the lowest risk. Regarding social factors, Peng et al. [16] focused on Shangsu County in Jiangxi, categorizing four types of fire points (grave sites, fireworks factories, temples, and ancestral halls) as cultural fire use. The results showed that grave sites had the most significant impact on fires, and there were numerous such sites. Areas with a high distribution of grave sites in Jinshan and Chishan towns were identified as extremely high-risk areas and focal points for fire prevention. Hou et al. [17] conducted a fire risk analysis at the pastoralist scale and found that areas with high values of permanent resident population, livestock quantity, and the combined area of houses and sheds were considered high-risk zones.

3.2. Disaster Dimension Fire risk Assessment

The disaster dimension of fire risk assessment studies the causes and development trends of wildfires. Song et al. [18] visually analyzed the causes and consequences of wildfires by constructing a wildfire disaster chain network model. They found that disaster events in the wildfire disaster chain network exhibited alternating evolution characteristics and were closely connected to other disaster events. Six critical disaster nodes in the wildfire disaster chain were identified, including gas station explosions and urban fires. Chuvieco et al. [19] considered fire spread and ignition as hazard factors, while social-economic factors, potential degradation degree, and landscape patterns were considered vulnerability factors. They constructed a dual-indicator fire risk assessment system. Ronchi and Jonathan [20-22] proposed the WUI-NITY modeling platform, which analyzes wildfire spread and human evacuation processes across three model layers: forest fires, pedestrians, and traffic. This platform can be applied for fire risk assessment and dynamic wildfire vulnerability assessment.

3.3. Construction of Fire risk Assessment Indicators

In both dimensions of fire risk assessment, the prerequisite is the construction of a reasonable set of indicators for the assessment of fire risk in the interface area. A fishbone diagram is employed to analyze fire risk in the interface area, as shown in Figure 1.

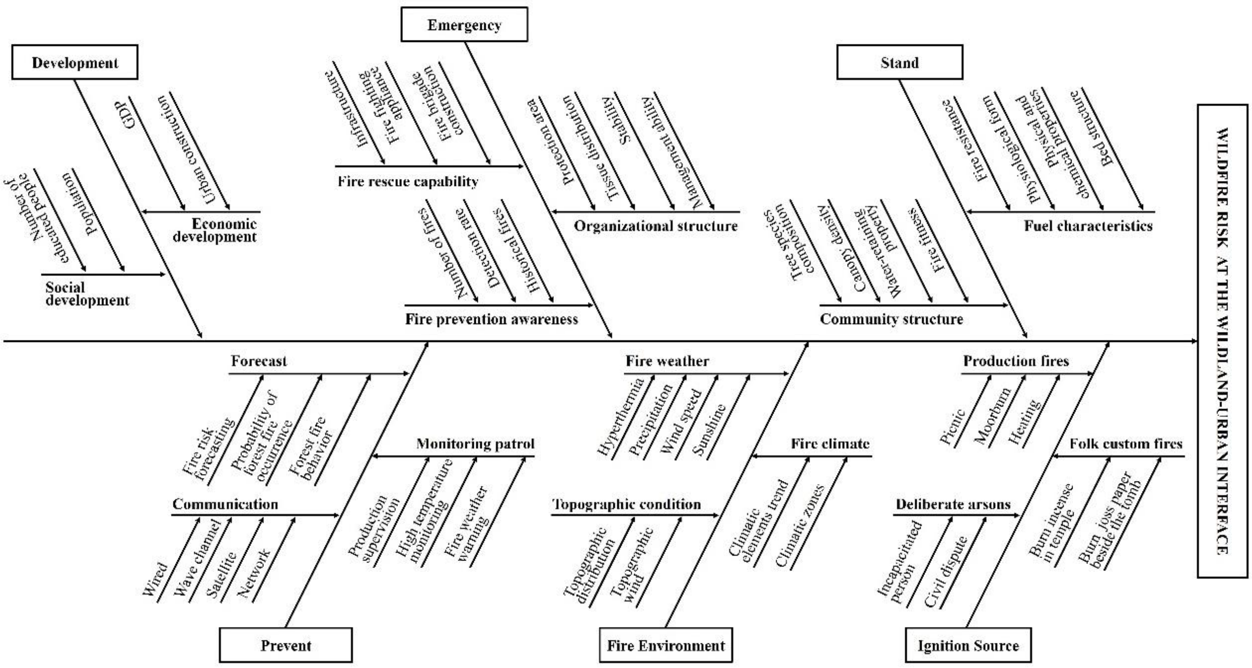

Figure 1. Fishbone map of fire risk at the WUI

3.4. Topology-Based Fire risk Assessment Methods

Topology originates from computer networks and is used to study the structural relationships between computers, communication devices, and transmission media. It is derived from topology in mathematics, which investigates methods independent of size and shape in terms of point and line relationships. Topological structures are categorized into five types: bus, star, ring, tree, and mesh. This paper, from the perspective of fire risk assessment, introduces two topology-based fire risk analysis methods: Fuzzy Comprehensive Evaluation (tree topology) and Bayesian Network Model (mesh topology).

3.4.1. Fuzzy Comprehensive Evaluation

Fuzzy Comprehensive Evaluation (FCE) is a comprehensive evaluation method based on fuzzy mathematics [23]. FCE transforms qualitative evaluations into quantitative evaluations based on the theory of membership in fuzzy mathematics. It quantitatively evaluates entities or objects subject to multiple influencing factors.

Let the m factors, denoted as u_i(i=1, 2, … m), that affect the evaluation result form the factor set U, where U={u_1, u_2, …, u_m}. Set n evaluation levels to form the evaluation set X, where X={x_1, x_2, …, x_n}. This establishes a mapping R from U to X, represented as:

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & . & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{mn} \end{bmatrix}$$

Generally, the m factors u_1, u_2, …, u_m differ in their importance for the evaluation. The varying importance of each factor u_i can be represented by assigining different weights a_i(i=1, 2, … m), forming the weight set A, i.e., A={a_1, a_2, …, a_m} (considered as a fuzzy set on the domain U). Additionally, the weight set A should satisfy normalization conditions. Therefore, in the process of comprehensive evaluation, by performing matrix operations between A and R, the fuzzy set B of the evaluation set X can be obtained. The final evaluation result is then derived using principles like the maximum membership principle or weighted averages.

The wildland-urban interface fires exhibit a degree of fuzziness, and hence, the Fuzzy Comprehensive Evaluation method can be applied to assess wildland-urban interface fires [24-25]. This approach allows for the consideration of the varying importance of different factors, making it suitable for the complex and uncertain nature of wildland-urban interface fires.

3.4.2. Bayesian Network Model

Bayesian Networks (BN), also known as belief networks, were proposed by Pearl in 1988 based on Bayesian decision methods [26]. They provide a statistical inference method for dealing with uncertainties in complex systems. BN combines qualitative and quantitative analyses, utilizing statistical data and prior knowledge to infer and acyclic graph, composed of variable nodes and directed edges connecting theseassess the studied system. The mathematical logic of a Bayesian Network is a directednodes. Nodes represent random variables, and directed edges between nodesrepresent their interdependencies (with parent nodes pointing towards their child nodes). The relationship between variables is expressed using conditional probability tables, and if a variable has no parent nodes, it is expressed using prior probabilities. Let G be a Bayesian Network defined on {X_1, X_2, …, X_N}, and its joint probability distribution can be represented as the product of conditional probability distributions for each node:

$$P(X_1, X_2, \ldots, X_N) = \prod_{i=1}^{N} P(X_i|Pa(X_i)) \tag{1}$$

Here, $Pa(X_i)$ represents the parent nodes of node X_i, and $P(X_i|Pa(X_i))$ is the conditional probability matrix for the node.

In 2010, Dlamini [27] used the Bayesian Network model for the first national forest and grassland fire risk assessment in Eswatini, and based on GIS and remote sensing data, generated a fire risk probability map, dividing Eswatini into five fire risk zones. This assisted relevant authorities in land management and policy formulation. Currently, the Bayesian Network model applied in forest fire risk assessment has seen improved accuracy and widespread use by combining statistical data on the main influencing factors in various assessment regions and refining modeling methods [28-30].

4. Prevention of Wildland-Urban Interface Fires

Preventing wildland-urban interface fires is currently a focal point and challenge in research. Experts, scholars, and government agencies worldwide actively explore methods for preventing wildland-urban interface fires. Zheng Wenxia et al. [31] summarized the emergency management system for wildland-urban interface wfires in the United States, covering aspects such as occurrence, prevention, and firefighting. Castillo et al. [32] calculated the minimum safe distance for wildland-urban interface fires in Chile and Spain. They also computed the radiative heat of potential fire behavior. The United States currently follows the International Wildland-Urban Interface Code, drafted in 2001, implemented in 2003, and most recently revised in 2018.

In China, fire prevention and control efforts generally follow regulations such as Code for Fire Prevention and Prevention of Rural area 2010, Forest Law of the People's Republic of China 2020, and Forest Fire Regulations 2008. No specific management measures are in place for the wildland-urban interface. According to official information from the Hebei Administration for Market Regulation [33], Hebei Province is soliciting public opinions on the local standard Guidelines for Fire Safety in Wildland-Urban Interface compiled by the Hebei Fire and Rescue Corps and the China People's Police University.

Fire prevention in the wildland-urban interface should consider the safety evacuation of residents. Zhou Jing et al. [34] compared evacuation methods proposed by different levels of government agencies in the United States, illustrating the roles and legal responsibilities of various agencies or organizations in ensuring the safety evacuation of residents in the event of wildland-urban interface fires. Folk et al. [35] established a Prevention Behavior Decision Model (PADM) based on seven factors, including population, social environment, and experience. This model combines public responses to wilfire events into a comprehensive wildland-urban interface fires evacuation model.

Regarding post-disaster disposal in the Wildland-Urban Interface, the United States suggests establishing fire-adapted communities for post-fire residential reconstruction, allowing residents to determine whether to rebuild or not [36-37]. Lopes et al. [38] analyzed the damage to industrial buildings and the building systems used for reconstruction after the 2017 forest fires in Portugal. This analysis supports the assessment of post-fire losses, economic and social recovery capabilities, and the fire resistance of building environments in the Wildland-Urban Interface.

5. Conclusion

The Wildland-Urban Interface is a complex environment, and once a fire occurs, it can easily lead to losses in social and economic development, posing a threat to human life. Drawing on the research findings of experts and scholars both domestically and internationally in the field of fire risk assessment and prevention in the wildland-urban interface, this paper summarizes and explains the causes and characteristics of wildland-urban interface fires. The following conclusions are drawn:

Causes of fires:The causes of wildland-urban interface fires involve both natural and social factors. Natural factors are related to the environment, while social factors are linked to human activities. Considering whether human activities directly influence the occurrence of wildfires, Social factors are further categorized into direct and indirect factors in the paper.

Characteristics of fires: wildland-urban interface fires exhibit characteristics such as abundant and continuous combustible materials, complex environments, multiple ignition points, large fire scales, rapid spread, and difficulty in firefighting.

Logical Framework for Fire risk Assessment:The logical framework for fire risk assessment in the interface area is established in two dimensions: regional and disaster. Regional dimension assessment focuses on specific regions or administrative areas, utilizing risk assessment methods to determine the level of fire risk and categorize risk levels for effective risk management. Disaster dimension assessment uses real or simulated fire events as examples, analyzing their causes and trends to guide directions for personnel evacuation and local fire risk management.

Challenges in fire Prevention: Some countries faces challenges in fire prevention in the wildland-urban interface, including weak fire prevention infrastructure, insufficient emergency management, and inadequate firefighting facilities. Understanding government regulations, local standards, evacuation and post-fire disposal practices in each country can provide valuable insights into strengthening local fire management.

In summary, there is room for improvement fire prevention in the wildland-urban interface. Strengthening fire prevention infrastructure, enhancing emergency management, and improving firefighting facilities are crucial steps in addressing the challenges posed by wildland-urban interface fires. In addition, countries' experience with government regulations, standards, evacuations and post-fire disposal can contribute to the enhancement and implementation of t local fire management.

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Declaration of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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