Forest fire rescue path network optimization combining multi-source remote sensing data and hierarchical analysis

Qinglie Yuan[a*]

[a] School of Civil and Architecture Engineering, Panzhihua University, Panzhihua 617000, China-*yuanqinglie@pzhu.edu.cn

Keywords: Forest Fire, Remote Sensing, Hierarchical Analysis, Landsat Imagery.

Abstract

Forest fires have exhibited an escalating trend in both frequency and intensity globally, with major and catastrophic events causing significant damage to forest resources, human lives, and property. Timely and accurate monitoring using multi-source remote sensing data presents an effective technological approach, substantially enhancing fire management efficiency and providing critical technical support for proactive prevention. Traditional manual field surveys are often inefficient and costly. Multi-source remote sensing data, characterized by their broad coverage, rapid update capabilities, and rich spectral information, hold immense potential for comprehensive forest fire monitoring. To facilitate prompt and precise rescue operations, this study utilizes Landsat 8 satellite imagery to analyze a specific fire event in Yuxi City, Yunnan Province, China. The methodology involves extracting active fire locations and simulating potential fire spread scenarios. We further integrate eight critical real-world influencing factors: slope, elevation, aspect, curvature, the Burn Index, vegetation index, proximity to roads, and distance to urban centers. Employing the Analytic Hierarchy Process (AHP), these factors were weighted and synthesized to assess the regional safety coefficient, generating a safety level map that functions as a minimum resistance surface. Subsequently, GIS-based spatial analysis techniques were applied to derive the minimum cost paths for evacuation and rescue access within the fire-affected area, stratified by the calculated safety levels. This process enabled the construction of an intelligent rescue path network. The results provide a robust theoretical framework and practical technical protocols for optimizing emergency response routing during forest fire incidents, enhancing both the safety and efficiency of rescue operations.

1. Introduction

Forests serve as pivotal components in maintaining ecological balance and represent indispensable resources for human survival and development. However, driven by extensive human activities and the variability of natural environments, forest fires occur frequently in sudden and unpredictable patterns (Abatzoglou et al., 2016; Anderson et al., 2025). As a severe threat to ecosystems, forest fires induce devastating consequences that cannot be overlooked. Uncontrolled fires can engulf dense forest areas within a short period, leading to ecological degradation and posing serious risks to public safety and social stability.

Forest fires spread rapidly once ignited, resulting in massive destruction of forest resources and severe damage to flora and fauna, which triggers a series of unpredictable ecological and social problems. Timely emergency rescue operations are essential after fire outbreaks, and the traffic conditions in affected areas exert a crucial impact on the efficiency of such operations. Due to these severe hazards, forest fires have become a global concern (Amarty et al., 2025; Guiop-Servan et al, 2025). To mitigate fire-induced losses and threats, extensive research on forest fire detection technologies has been conducted worldwide. Understanding the causes of forest fires and advancing detection technologies are key to enhancing fire prevention efforts and improving fire point detection accuracy.

Satellite remote sensing technology acts as a core tool for acquiring surface and atmospheric information, facilitating the rapid development of research on atmospheric pollutant emissions and satellite-based fire monitoring. This technical system integrates low-earth orbit satellite constellations, high-altitude long-endurance UAVs and other monitoring equipment to establish a technical chain covering data acquisition, transmission, processing and intelligent analysis. It effectively improves fire point positioning accuracy and fire development prediction efficiency (Masoudian, et al., 2025).

Geographic Information System (GIS) leverages its spatial processing capabilities to integrate meteorological parameters, vegetation change trends, surface morphological characteristics and other multi-source data (Smith-Tripp et al., 2025; Tian et al., 2025). It enables accurate assessment of forest fire occurrence probabilities and provides technical support for intelligent fire early warning systems. Against this technical backdrop, this study focuses on the forest ecological zone in Yuxi City, Yunnan Province, China.

The research constructs an early warning and emergency decision analysis for forest fires by fusing multi-source remote sensing images with remote sensing GIS technologies. An improved path optimization algorithm is embedded in the system to shorten disaster response time. Severe forest fires in this region have caused compound consequences, posing grave threats to local residents' lives and exerting far-reaching impacts on Yuxi's socio-economic order and ecological environment.

Although hierarchical emergency plans were implemented immediately after previous fire disasters, the actual rescue effectiveness remained unsatisfactory due to the combined effects of irregular fire spread and complex terrain. Research data indicates that the expansion of urban-rural construction land and intensified human interference have brought new challenges to forest fire defense. The establishment of a

https://doi.org/10.5194/isprs-archives-XLVIII-M-10-2025-249-2026

comprehensive sensor network collaborative monitoring system is therefore imperative.

This study innovatively integrates diversified remote sensing detection technologies with geospatial information platforms to develop the forest fire intelligent early warning and emergency path decision system. By combining multi-source remote sensing data with remote sensing-GIS technologies, the system realizes dynamic monitoring of fire zone evolution characteristics. It provides high-precision situational information for disaster command centers, thereby improving the response speed to sudden fire events. This research is expected to fill the gaps in current fire prevention and control systems for complex forest areas and offer technical references for global forest fire management.

2. Method

This study extracted and analyzed multiple topographic parameters including slope, aspect, curvature variation and elevation based on the digital elevation model (DEM) datasets, and generated corresponding thematic maps for each parameter. These spatial analysis results not only enhance the interpretation accuracy of remote sensing images but also reveal the intrinsic correlations between topographic factors and forest fire spread, thus providing theoretical support for fire point localization (Tian et al., 2025). The technical workflow of the entire methodology is presented in Figure 1.

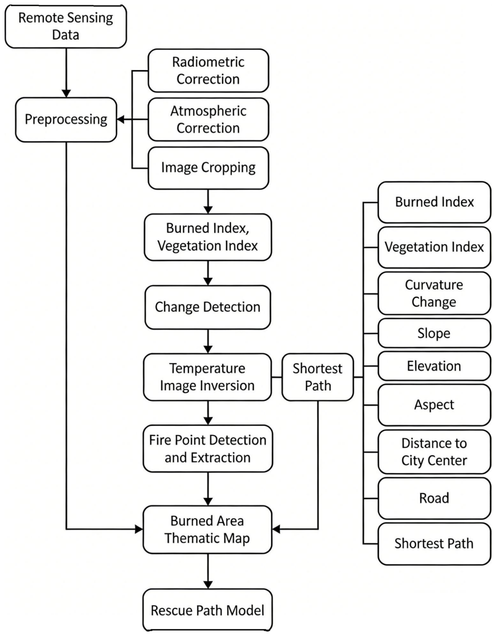


Figure1. Methodology workflow graph.

Specifically, the slope parameter reflects the steepness of the terrain and enables the prediction of fire spread directions. Aspect characteristics, combined with vegetation distribution patterns, support the analysis of wind's promotional effects on fire development. Elevation data depicts the variation law of temperature with altitude, while curvature variation characterizes the intensity of topographic morphological impacts on fire propagation. In addition, the potential fire impacts on human settlements are assessed by calculating the spatial distance from fire-prone areas to residential clusters, and the distribution of transportation networks is analyzed to provide references for rescue route planning. This comprehensive spatial analysis framework achieves the quantitative evaluation of fire risks from a topographic perspective, and further offers critical spatial decision-making evidence for forest fire prevention and emergency response.

The Analytic Hierarchy Process was integrated in this research to determine the weight values of each influencing factor by comprehensively evaluating their relative impact severity, and the rescue safety grade map of fire-affected areas was generated accordingly. Based on the safety grade map, the minimum cumulative resistance surface was constructed by incorporating the distribution of water sources and urban settlements, which provides scientific basis and technical support for rescue route planning. The optimal rescue route was screened out from a set of generated alternative routes using GIS spatial analysis tools.

2.1 Burned Area Detection

This study employed the burn characteristic index method for burned area extraction, with the specific technical workflow referring to Section 3.3. Two typical indices were adopted for burn severity assessment, namely the Burned Area Index (BAI) and the Normalized Burn Ratio (NBR). The formula for BAI is expressed as Equation (1).

$$BAI = \frac{1}{\left(\mathrm{Re}d - 0.06\right)^2 + \left(NIR - 0.1\right)^2} \tag{1}$$

where BAI denotes the Burned Area Index, Red represents the red band (e.g., Band 4 of Landsat 8/9 satellites), and NIR stands for the near-infrared band. The formula for the Normalized Burn Ratio is given in Equation (2).

$$NBR = \frac{\left(NIR - SWIR2\right)}{\left(NIR + SWIR2\right)} \tag{2}$$

For the NBR calculation, reflectance data from the near-infrared (NIR) spectral range and shortwave infrared (SWIR) spectral range (Band 7) are required. In burned area identification, the BAI demonstrates superior detection capability, while the NBR provides finer discrimination in evaluating fire severity levels.

2.2 AHP and MCR Model

The Analytic Hierarchy Process (AHP) is a multi-criteria decision-making method designed to solve complex decision problems. As a structured decision analysis approach, it integrates qualitative and quantitative techniques by considering the combined effects of multiple factors (indicators) across hierarchical levels. The core procedure of AHP involves constructing a hierarchical structure, establishing pairwise comparison matrices, calculating factor weights, conducting consistency tests, and ultimately quantifying the relative importance of each factor in the decision-making process. This method decomposes complex problems into a hierarchical framework, which typically includes a goal layer, a criterion layer, and an alternative layer. Pairwise comparisons of influencing factors are performed using the 1 – 9 scale method to quantify their relative importance, followed by weight calculation and consistency testing of the comparison matrices to ensure logical rationality. The mathematical modeling steps of the AHP are as follows:
(1) Construction of the hierarchical model. A three-level framework is established to address complex decision problems.

The top goal layer focuses on the core objective, such as "optimal scheme selection". The middle criterion layer integrates key factors including cost-benefit, performance indicators, and operational feasibility. The bottom alternative layer presents all optional solutions. This hierarchical design realizes the scientific decomposition and systematic integration of multi-dimensional decision factors through a goal-oriented vertical correlation system.

(2) Establishment of pairwise comparison matrices. Elements within each layer are compared pairwise. This scale converts subjective judgments on factor importance into measurable numerical values, laying a foundation for subsequent weight calculation.

(3) Calculation of weight vectors. Factor weights are calculated using either the eigenvalue method or the geometric mean method. These methods transform the information in the pairwise comparison matrices into quantitative weights that reflect the relative importance of each element.

(4) Consistency test and weight synthesis. The consistency test is conducted to verify the logical rationality of the pairwise comparison matrices, eliminating contradictions caused by subjective judgments. Subsequently, weights of each layer are synthesized step-by-step to calculate the total weight of each alternative relative to the top goal layer. The alternative with the highest total weight is selected as the optimal solution.

The Minimum Cumulative Resistance (MCR) model, as an innovative spatial analysis tool integrating quantitative evaluation and geovisualization capabilities, has gradually evolved into a core technical method for ecological security pattern construction, enabling accurate simulation of the diffusion features of various ecological processes in two-dimensional space. This study adapts this method for constructing the rescue network model, where a resistance surface is established based on multiple factors, and the minimum resistance path is identified as the optimal rescue route.

The theoretical framework of the MCR model comprises three core components: identification of source-sink patterns, which clarifies the spatial distribution characteristics of biological migration paths and human activity impacts; calculation of resistance values, which quantifies the total obstacles encountered by biological movement across various landscape elements; and determination of optimal paths, which identifies the best corridors for spatial connectivity. Its mathematical expression is given in Equation (3).

$$MCR = f_{min}\left(\sum_{j=n}^{i=1} D_{ij} \times R_i\right)n \tag{3}$$

where D_{ij} represents the spatial distance from source i to a specific point j;

Ri denotes the resistance of source i during spatial expansion;

$\sum$ indicates the cumulative sum of distances and resistances across all landscape element units from source i to point j;

f_{min} represents the positive correlation between the minimum cumulative resistance and ecological/human processes;

MCR is the minimum cumulative resistance value.

3. Experimental Data Preprocessing

3.1 Overview of the research area

The study area is situated in Yunnan Province of southwestern border of China. Endowed with a low-latitude plateau terrain, Yunnan features diverse climatic patterns and complex geomorphic configurations. Under the influence of monsoon circulation, it is dominated by continental dry cold air in winter and maritime warm humid air in summer, forming distinctive plateau mountain monsoon climate characteristics. Specifically, the research focuses on Yuxi City, which lies in the transition zone from the Yunnan-Guizhou Plateau to western Yunnan. Spanning the Ailao Mountain Range. Yuxi constitutes a complex geomorphic system interweaved with mountains, valleys and lakes, as shown in Figure 2. Its administrative area covers 15,300 square kilometers, accounting for approximately 3.8% of Yunnan Province's total area.

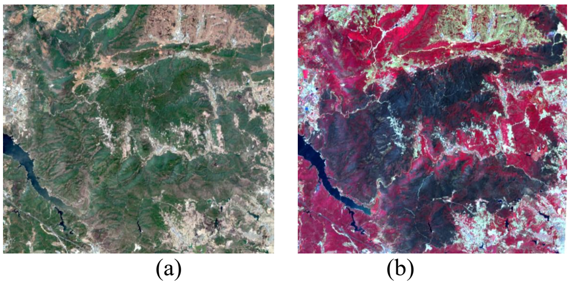


Figure 2. Overview of the research area. (a) is true color image and (b) is the is the pseudo-color image using the near-infrared, red and green bands.

Within Yuxi City, the focus of this study is Jiuxi Town in Jiangchuan District, located on the western edge of the Central Yunnan Plateau. Mountains occupy over 60% of the town's total area, presenting a typical mountainous landscape characterized by overlapping peaks and crisscrossing gullies. Jiuxi Town is adjacent to Dajie Sub-district in the east and Yi ethnic communities in the south. The terrain slopes from high in the northwest to low in the southeast, with an elevation ranging from 1,700 meters to 2,200 meters above sea level.

3.2 Data Preprocessing

This study took Landsat 8 satellite data acquired on April 16, 2023 as the primary information source. It utilized the shortwave infrared band combination of Bands 8, 4, and 3 to generate false color composite images, thereby accurately extracting the outline of the Yuxi forest fire-burned area. To improve research accuracy, Sentinel-2 Level-2 data subjected to geometric precision correction and radiometric calibration was selected for verification. Landsat 8 image preprocessing has been completed, including radiometric calibration, atmospheric correction, and image cropping, as shown in Figure 3.

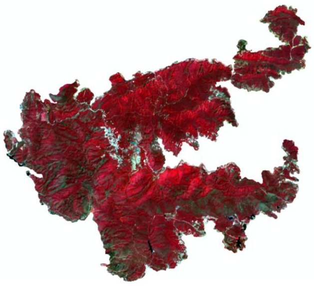


Figure 3. The cropped pseudo-color image using the near-infrared , red and green bands.

Land surface temperature retrieval is commonly implemented via three mainstream methods: the Atmospheric Correction Method (Radiative Transfer Equation method), the Single-Window Algorithm, and the Split-Window Algorithm. All three methods require at least two key input parameters for reliable retrieval results: atmospheric profile parameters, with atmospheric transmittance as the core index, and land surface emissivity. This study adopted the theoretical framework of the Atmospheric Correction Method for land surface temperature retrieval.

4. Experimental results

4.1 Forest fire point detection

As illustrated in the Figure 4, the fire point extraction process commences with focal statistics applied to the temperature dataset. To obtain the image that optimally reflects temperature variations, multiple statistical radii were tested. The optimal image was determined through comparative analysis of results derived from different radii.

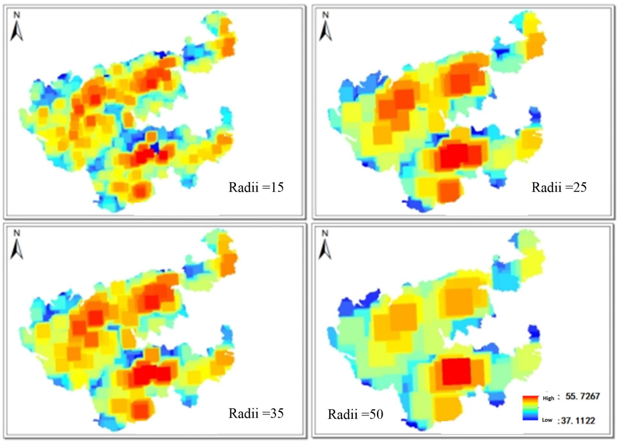
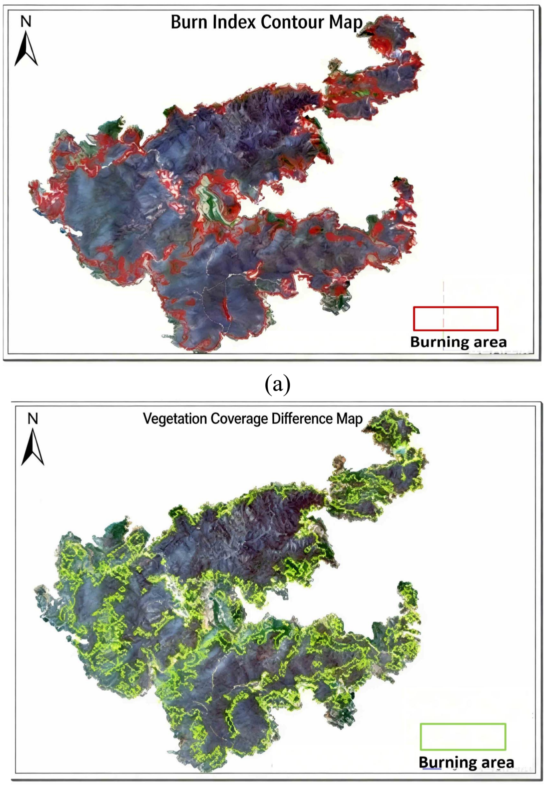


Figure 4. Extraction fire-points using focus statistical from LST maps with radii of 15, 25, 35, and 50.

Subsequently, high-temperature points were extracted, and their corresponding temperature values were calculated. Candidate fire points were further screened based on relevant influencing factors, ultimately generating a temperature map with identified fire points. This map provides a critical foundation for the subsequent optimal rescue route planning.

4.2 Forest fire change detection

Figure 5 presents thematic maps generated from different detection results of the forest fire-affected area, which comprehensively and intuitively characterize the fire-affected scope from distinct detection perspectives. These maps consist of two feature difference components: NBR and normalized difference vegetation indices (NDVI) before and after fire occur. The maximum temperature points of the identified fire zones, derived from the previous land surface temperature retrieval, were cross-referenced with all detection outputs for verification. The validation results indicated that although minor discrepancies existed in the boundary delineation of fire-affected areas among different detection methods, the identification of the central high-temperature fire zones was generally consistent across all approaches.



(a)

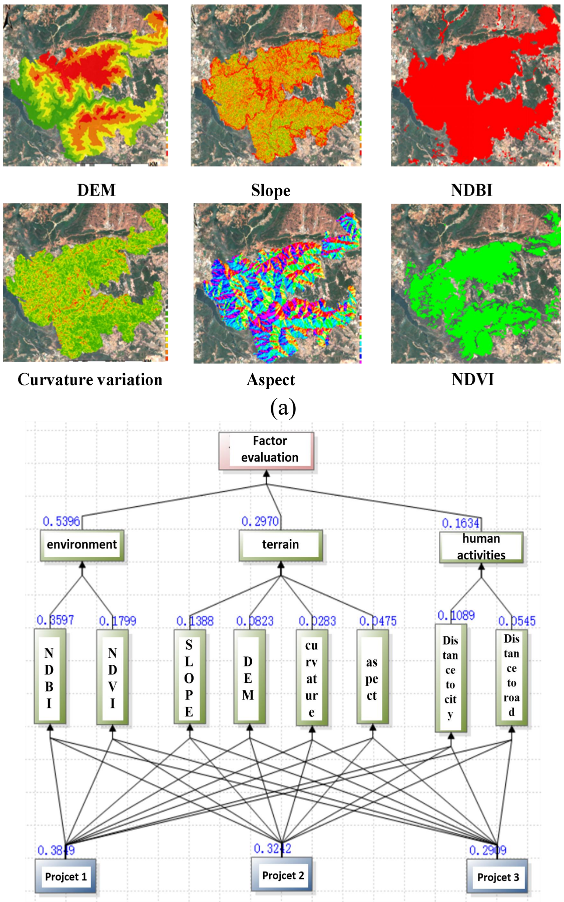
(b)

Figure 5. Forest fire burning area detection of Yuxi city using NDVI in (a) and NBR in (b)

Notably, the disaster range extracted based on burn indices achieved a high degree of consistency with manually interpreted reference data. In contrast, the vegetation index-based method exhibited considerable deviations in extraction results, with its integrity and accuracy of identified fire ranges being significantly lower than those of the burn index approach. These experimental comparisons fully demonstrate that burn indices possess prominent technical advantages for analogous forest fire monitoring applications.

4.3 Forest Fire Rescue Network Modeling

Considering the actual geographical conditions of the study area, elevation, slope, aspect, curvature variations, vegetation indices, and burn indices can adequately characterize its natural landscape. Among these indicators, elevation, slope, aspect and curvature variations are associated with the topographic composition of the study area, and exert a direct influence on the difficulty and feasibility of rescue route design. Specifically, higher elevation, steeper slope, windward aspect and significant curvature variations will increase the difficulty of rescue operations, while the opposite conditions will reduce such difficulty. Meanwhile, vegetation indices exhibit a positive correlation with fire hazard potential, and thus constitute one of the core components of the fire safety evaluation index system in this study. The weights of different factors can be determined using the AHP algorithm, as shown in Figure 6.

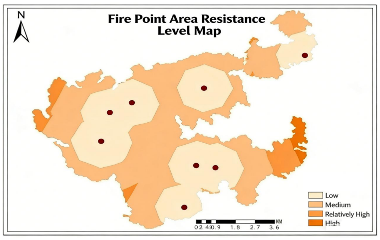


(b)

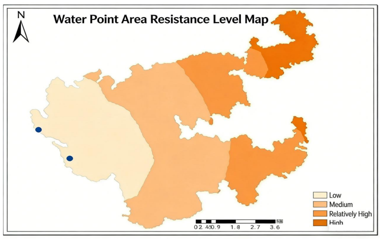
Figure 6. Assessment of Impact Factors on Forest Fire Rescue Network Security. (a) is the factor visualization results (b) is the weight coefficient model using AHP.

The resistance surface characterizes the spatial process of rescue accessibility (adapted from the ecological process of species diffusion), representing the minimum cumulative cost of the process from source points to target fire areas. Taking the source points as the feature data, the cost raster data was derived from the safety grade map of the fire-affected area. The resistance factors adopted the safety-influencing factors that had been weighted via the Analytic Hierarchy Process (AHP) as mentioned above.

Beyond the generated safety grade map, the impacts of source locations and spatial distance were incorporated. All source points were taken as feature source data to generate cost distance raster data and extract the minimum resistance surface. To unify the data format, the natural breaks classification method was employed to reclassify the resistance surface into four levels with low, medium, relatively high, and high based on the comprehensive resistance magnitude, as presented in Figure 7.



(a)



(b)

Figure 7.Resistance surface levels. (a) is the fire resistance level and (b) is the water point resistance level.

Based on the established resistance surface model, path analysis was conducted by designating eight primary unextinguished fire point zones as target points, and two water source zones plus two urban settlement zones as starting points. Notably, water source zones served both as starting points and target water collection points, necessitating multiple path connections between these sites. Feasible rescue routes in the study area were identified through the overlay of multi-scenario path results and elimination of redundant paths. By integrating the analysis results with the actual road distribution in the study area, a total of 38 potential rescue routes were ultimately determined. The remaining areas within the study domain are mountainous terrain with no accessible road networks, as presented in Figure 8.

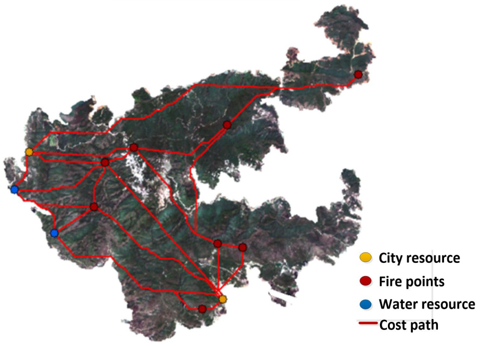


Figure 8. Forest fire safety network modeling.

5. Conclusion

This study integrates multi-source remote sensing technology, AHP and MCR models to conduct systematic research on forest fire monitoring and rescue path optimization in Jiuxi Town, Yuxi. It accurately detects fire points and burned areas via BAI and NBR indices, constructs a resistance surface based on topographic and ecological factors, and ultimately identifies 38 potential rescue routes. Results verify the reliability of burn indices in fire detection and the feasibility of the integrated model in route planning. This research provides practical technical protocols and decision-making support for emergency response in mountainous forest fires, while its framework can be adapted to similar fire-prone regions, contributing to improved global forest fire management efficiency.

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