

Research on the Comprehensive Forest Fire Monitoring System in Central Yunnan Based on Satellite Monitoring Hotspot Data and Smoke Collection Devices

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Abstract: Central Yunnan, as a major urban agglomeration in Yunnan Province, is characterized by the interplay of complex topographic conditions, highly flammable vegetation, and frequent human activities, making it a high-incidence area for forest fires and a challenging zone for prevention and control. Traditional monitoring methods that rely solely on satellite remote sensing or ground-based observations are constrained by insufficient spatiotemporal resolution and limited coverage, making it difficult to achieve early and accurate forest fire warning. In recent years, multi-source monitoring strategies integrating satellite hotspot data and ground-based sensor networks have emerged as a key pathway to enhance forest fire early warning capabilities. This paper systematically reviews the research progress of the integrated forest fire monitoring system in Central Yunnan, focusing on the spatiotemporal distribution patterns and trend prediction methods derived from satellite hotspot data such as MODIS and VIIRS, revealing the spatiotemporal coupling characteristics of forest fires—high incidence in spring and winter, and clustering around coniferous forest belts and road networks. Meanwhile, it elaborates on a self-developed smoke and dust collection device suitable for the complex plateau environment, which integrates laser scattering sensing, LoRa spread-spectrum communication, and solar-powered long-duration power supply modules, enabling real-time collection and long-distance transmission of multiple parameters including PM_{2.5}, temperature, and humidity. On this basis, a three-level early warning model based on the random forest algorithm and an LSTM trend prediction model are constructed. Through multi-source data fusion and spatiotemporal alignment, the early warning response time is shortened to within one hour, and the fire detection efficiency in pilot areas has increased by 60%. The study points out that future efforts should further optimize data acquisition frequency, improve model generalization under extreme climatic conditions, and expand device deployment density to achieve precise and dynamic control of fire risks in Central Yunnan and even the broader southwestern forest regions.

Keywords: Forest fire monitoring; satellite hotspot data; smoke dust collection device; central Yunnan; data fusion.

1. Introduction

Forest fires are one of the major natural disasters that occur frequently worldwide. Different from urban fires, forest fires mostly break out in open and remote forest areas, making them difficult to detect at the early ignition stage. Driven by relatively continuous combustibles and complex terrain, forest fires can easily escalate into large-scale uncontrollable fires, and fire suppression is significantly restricted by wind direction and topography^[1]. The main factors influencing the occurrence of forest fires include meteorological factors, topographic factors, vegetation factors and human factors^[2]. China is a country prone to forest fires. From 1989 to 2019, the annual average number of forest fires reached 6,505, with an average annual affected area of nearly 70,000 hectares^[3]. As the central urban agglomeration of Yunnan Province, central Yunnan integrates a special geographical environment, complex climatic conditions, highly flammable coniferous forests (Yunnan pine and Armand pine account for 60%) and high-intensity human activities, resulting in frequent forest fires and difficult fire suppression in the region. The limitations of traditional single monitoring methods have become increasingly prominent^[4].

Scholars at home and abroad have carried out a series of studies on forest fire monitoring technologies. In terms of satellite remote sensing, fire products such as MODIS and VIIRS have been widely used in large-scale fire point identification, but they are subject to satellite transit cycles

and cloud interference, leading to time delays and spatial errors. Fasullo et al. confirmed through simulation that human factors can alter meteorological conditions and thus exacerbate fire risk^[6]. Robinne et al. introduced human factors such as road density and energy networks to establish a regional fire risk model^[7]. In China, Zhao Pengwu et al. conducted fire risk zoning based on population and road network density; Wang Jin et al. compared the performance of algorithms such as LSTM and random forest in forest fire prediction. Both studies indicate that the integration of multi-source data and machine learning models is an effective approach to improve prediction accuracy.

However, current studies mostly focus on the driving effects of single data sources or static factors, lacking an in-depth exploration of the dynamic coupling mechanism between satellite monitoring data and real-time ground smoke information. In particular, there is a lack of systematic construction of a space-ground integrated monitoring system for complex terrain areas in central Yunnan. In response to this, based on the practical needs of forest fire prevention and control in central Yunnan, this paper integrates satellite hotspot data and independently developed smoke collection devices to propose a comprehensive monitoring system covering data collection, fusion processing, and early warning and prediction. The research aims to reveal the spatiotemporal distribution patterns of forest fires, screen core disaster-causing indicators, verify the practical effect of multi-source data fusion on improving the timeliness and accuracy of early

warning, and provide a replicable technical scheme for forest fire prevention in complex terrain areas.

2. Research Contents and Methods

2.1. Research Contents

2.1.1. Acquisition and Analysis of Satellite Monitoring Hotspot Data

Remote sensing satellite hotspot monitoring data were obtained for central Yunnan, mainly including fire products from satellites such as MODIS and VIIRS, covering key information including latitude and longitude coordinates, precise timestamps, and fire radiative power of forest fire occurrences. In the data preprocessing stage, false fire points were removed through radiometric calibration, geometric correction, cloud detection, and threshold methods (e.g. brightness temperature > 310K). Time series decomposition was employed to analyze the distribution differences of forest fires across seasonal alternation, monthly variation, and diurnal shifts. Combined with a digital elevation model (DEM), the spatial differentiation patterns were examined at different elevation gradients (1000–3000 m), slope classes (0°–60°), and slope aspects (sunny/sloped and shaded slopes). A kernel density estimation model was used to calculate hotspot density, and Moran's I index and Getis-Ord G_i^* statistic were applied to reveal spatial clustering characteristics, systematically exploring the spatial evolution trends and interannual fluctuation intensity of forest fires [6].

2.1.2. R&D of Smoke Collection Device

An intelligent smoke collection device integrating multi-parameter monitoring functions was developed. A laser scattering sensor was adopted to monitor PM2.5/PM10 concentrations (measuring range: 0–1000 $\mu\text{g}/\text{m}^3$, accuracy: $\pm 3\%$), ambient temperature (-20°C to 60°C), and relative humidity (0–95% RH). LoRa spread-spectrum communication technology was used for data transmission, enabling stable transmission over 5 km in dense forest areas to ensure real-time data return to the processing center. In terms of structural design, the device adopted an IP66-rated enclosure, capable of withstanding Grade 10 wind impacts, adapting to the complex alpine forest environment with large diurnal temperature variations, frequent fog, and rainfall. The power supply module combined a 10 W monocrystalline silicon solar panel and a 12 V/20 Ah lithium iron phosphate battery, supporting 30 consecutive days of operation under cloudy and rainy conditions. The standby power consumption was controlled below 8 mA through a sleep-wake mechanism, fully meeting the requirements of low power consumption and long-term monitoring [12].

2.1.3. Construction of a Comprehensive Forest Fire Monitoring System

Satellite monitoring hotspot data and data obtained from smoke collection devices were integrated to establish a data fusion model, realizing the complementarity and coordination of multi-source data. Forest fire early warning models and trend prediction models were constructed to predict the probability and development trend of forest fires in advance based on monitoring data and influencing factors. The architecture of the comprehensive monitoring system was designed, including a data acquisition layer, data processing layer, early warning and decision-making layer, and application layer, realizing all-round monitoring and management of forest fires [13].

2.1.4. Screening of Key Indicators Affecting Forest Fire Occurrence

Combining satellite-monitored fire location and intensity data with multi-dimensional data such as geography, climate, vegetation, and human activities, core indicators influencing forest fire occurrence were systematically screened. For geographical environment, topographic factors including elevation (graded at 1000–3000 m intervals), slope (0°–60°), and aspect (sunny slope/shady slope/flat slope) were prioritized, as they directly affect fuel drying rate and fire spread direction. Climatic conditions were refined into daily average temperature, relative humidity, monthly precipitation, 10-minute maximum wind speed, and number of extreme high-temperature days ($\geq 30^\circ\text{C}$), which dominate fire risk levels by regulating vegetation moisture content and combustion conditions. Vegetation characteristics focused on coniferous forest coverage (Yunnan pine and Armand pine, accounting for 60%, are highly flammable species) and fuel load (litter thickness > 5 cm as a high-risk threshold). Human activities were quantified by population density (areas ≥ 250 people/ km^2 as key zones), road network density (over 60% of fire points within 1 km of roads), and average daily tourist flow during peak seasons, reflecting the intensity of human-caused fire sources. Through a three-stage screening process—Pearson correlation analysis ($|r| > 0.5$), principal component analysis for dimensionality reduction (cumulative contribution rate $\geq 85\%$), and random forest importance evaluation (sorted by Gini coefficient)—12 core indicators were finally determined. Among them, air temperature (weight 22%), coniferous forest coverage (18%), and road density (15%) were the most critical driving factors, accurately reflecting the fire formation mechanism in central Yunnan characterized by “dry climate, flammable vegetation, and concentrated human disturbance” [14].

2.2. Research Methods

2.2.1. Data Collection Methods

Remote sensing satellite data for central Yunnan were obtained through channels including the National Satellite Meteorological Center and remote sensing satellite ground stations, including hotspot monitoring data from MODIS, NOAA, and other satellites [15]. Team members conducted field surveys in forest areas of central Yunnan to collect information on local geographical environment, vegetation types, and fire source distribution, while inspecting and selecting installation locations for smoke collection devices [16]. Relevant experiments were carried out in the laboratory to test performance parameters of the smoke collection device, such as collection efficiency and data transmission stability. Forest fire simulation experiments were conducted to study the occurrence and spread of forest fires under different conditions [17].

2.2.2. Data Analysis Methods

Geographic information system software such as ArcGIS was used to analyze the spatial distribution of forest fires, including spatial interpolation, buffer analysis, and overlay analysis, revealing spatial distribution characteristics and patterns [18]. Statistical software such as SPSS was used to perform statistical analyses on time-series data of forest fire occurrence and influencing factor data, including descriptive statistics, correlation analysis, and regression analysis, to screen key influencing indicators and construct prediction models [19].

Data fusion algorithms were adopted to integrate satellite

monitoring data and smoke collection data, eliminating data redundancy and conflicts and improving data reliability and consistency^[20]. Functional requirements and performance indicators of the smoke collection device were defined according to practical forest fire prevention needs^[12]. Based on demand analysis, the overall structure, hardware composition, and software algorithms of the device were designed, including sensor selection, data transmission module design, and power management scheme^[21]. A prototype was fabricated and tested in laboratory and field environments, and the design was optimized according to test results to improve performance and stability^[22].

Machine learning algorithms such as support vector machines and neural networks were used in the early warning model. With the screened key indicators and monitoring data as inputs, a forest fire early warning model was constructed to realize early warning of forest fire occurrence^[23].

The trend prediction model adopted time-series analysis methods such as the ARIMA model and grey prediction model. Combined with historical forest fire data and current monitoring data, a forest fire trend prediction model was established to forecast the occurrence trend and scale of future forest fires^[4].

3. Results and Prospects

3.1. Results of Satellite Hotspot Data Analysis

Analysis of satellite monitoring hotspot data revealed the spatiotemporal distribution patterns of forest fires in central Yunnan. Temporally, forest fires exhibited obvious seasonality, mainly concentrated in spring and winter, when the climate is dry and precipitation is scarce, making fires prone to occur. Diurnally, fires mostly occurred during the daytime, especially in the afternoon, related to human activities and rising temperatures. Spatially, fires were mainly distributed in areas with low elevation and gentle slopes, where human activities are frequent and fire sources are abundant. Fires were also concentrated in coniferous forest zones due to high fuel flammability^[6].

Hotspot density in central Yunnan was calculated, showing that high-density areas were mainly concentrated at the interface between forests and human activity zones, such as forest edges and near roads. Spatial clustering analysis indicated that forest fires displayed significant spatial aggregation, forming multiple high-incidence zones requiring key prevention and control^[18].

Analysis of spatial change trends showed that in recent years, the range of forest fires has tended to expand to higher elevations, possibly related to climate warming. Meanwhile, spatial fluctuations were significant, strongly affected by climatic conditions and human activities^[3].

A smoke collection device for forest fire prevention was successfully developed, mainly composed of a smoke sensor, data acquisition module, wireless transmission module, power module, and enclosure. The smoke sensor adopted a high-precision optical sensor to accurately detect smoke concentration in the air. The data acquisition module collected and preprocessed sensor data in real time. The wireless transmission module used LoRa technology to achieve long-distance transmission over 5 km. The power module combined solar panels and batteries to ensure long-term stable operation in the field^[12].

Performance characteristics: Measuring range: smoke concentration 0–1000 mg/m³, accuracy ±5%. Operating environment: temperature –20°C–60°C, humidity 0–95% RH (non-condensing) Power consumption: standby <10 mA, operating <50 mA Protection class: IP65, resistant to rain and dust

A data fusion model for satellite and smoke collection data was established in the comprehensive monitoring system. Through spatiotemporal registration, feature extraction, and weight assignment, effective data fusion was realized. The fused dataset more comprehensively reflects fire development and improves monitoring accuracy^[13].

A multi-level early warning system and medium-to-long-term trend prediction model system were constructed. The early warning model took real-time monitoring data (PM2.5 concentration and change rate from smoke devices, satellite hotspot temperature) and 12 core indicators as inputs, using an improved random forest algorithm optimized by 5-fold cross-validation (200 decision trees, maximum depth 15 layers), realizing minute-level real-time calculation. Three-level warning thresholds were set: Comprehensive risk index >60: orange warning (fire likely within 1 hour) 80: red warning (high risk within 30 minutes)

In pilot forests such as Mopan Mountain and Pearl River Source in central Yunnan, early warning accuracy reached 89%, with false alarm rate below 7%, providing warnings 1.5–2 hours earlier than traditional methods^[23].

The trend prediction model integrated nearly 10 years of historical fire data, quarterly climate forecasts (e.g., ENSO index, monsoon intensity), and vegetation phenology characteristics. It used an LSTM neural network combined with STL time-series decomposition to separate long-term trends (driven by warming), seasonal fluctuations (high incidence in dry seasons), and random disturbances (sudden human-caused fires). The model outputs 1 km × 1 km spatial fire risk distribution maps and high-incidence period forecasts for 1–3 months ahead. For example, it predicted that fire risk in the high-altitude coniferous belt of northern central Yunnan in March would be 20% higher than normal, providing a quantitative basis for quarterly prevention planning, including allocating 30% more fire-fighting equipment and increasing patrol frequency from twice to four times per week^[23].

A comprehensive forest fire monitoring system for central Yunnan was designed and developed, including four functional modules: data acquisition, data processing, early warning and decision-making, and application. The system receives and processes satellite and smoke data in real time, generates warnings and prediction reports, and displays them visually to support decision-making by fire management departments^[20].

3.2. Research Prospects

This project successfully constructed a comprehensive forest fire monitoring system for central Yunnan through satellite hotspot analysis and smoke collection device development. The research revealed spatiotemporal distribution patterns, screened key indicators, developed a high-performance smoke device, built high-precision early warning and prediction models, and achieved good results in pilot applications^[11].

During implementation, the team gave full play to professional advantages, cooperated in division of labor,

overcame difficulties in data acquisition and technical bottlenecks, and completed preset research objectives. Scientific research, practical, and teamwork abilities were significantly improved^[16].

Limitations: Data acquisition and updating: Satellite data are affected by transit time and weather, leading to time delays and missing values. The limited number of smoke devices results in insufficient coverage and reduced spatial representativeness^[15].

Model accuracy and adaptability: Although model accuracy is acceptable, adaptability under extreme climates needs further verification. Generalization ability is limited and requires adjustment for other regions^[4].

Device performance optimization: Sensor drift and component aging may occur during long-term operation, affecting data stability. High costs hinder large-scale promotion^[22].

Future work: Expand data channels to obtain higher-resolution and higher-frequency satellite data; increase the number of smoke devices, expand coverage, and establish data sharing mechanisms^[15].

Optimize early warning and prediction models by introducing deep learning and big data analytics; strengthen validation and update parameters based on actual fire data^[19].

Improve device performance, reduce costs, enhance durability, and develop new sensors and transmission technologies for intelligent remote diagnosis and maintenance^[21].

Promote the comprehensive system across central Yunnan, then to other regions of Yunnan and nationwide; strengthen cooperation with fire departments and research institutions to enhance application effects^[9].

Through continuous improvement, the comprehensive monitoring system is expected to be further refined, providing stronger technical support for forest fire prevention, effectively protecting forest resources, and promoting sustainable ecological development^[3].

4. Innovations of the Project

4.1. Technical Innovation

Multi-source data fusion technology: Fusion of satellite hotspot data and ground smoke data combines the wide coverage of satellites and high real-time performance of ground monitoring, realizing all-round high-precision forest fire monitoring and improving accuracy and reliability^[13].

Novel smoke collection device: The developed device features low power consumption, high stability, and adaptability to complex environments. Solar power supply and LoRa wireless transmission solve power supply and data transmission challenges in field monitoring, enabling real-time and accurate smoke information collection^[12].

4.2. Methodological Innovation

Comprehensive monitoring system construction method: An integrated system covering data acquisition, processing, early warning, and prediction was constructed, organically combining multiple technologies to form a complete solution for systematic fire prevention support^[20].

Indicator screening and modeling method: Multi-source data and statistical methods were combined to screen key fire

indicators, and machine learning-based early warning models and time-series prediction models were established to improve prediction accuracy^[19].

4.3. Application Innovation

This study targeted the fire characteristics and prevention needs of central Yunnan, resulting in a highly targeted and practical monitoring system that effectively solves local monitoring problems^[7].

The developed device and system provide a reference for forest fire monitoring in other regions, with broad promotion prospects and significance for advancing national forest fire prevention technology^[10].

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