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Research on Forest Fire Prognosis based on Multi-Source Data

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Abstract. The occurrence of forest fires not only destroys the ecological balance and devours valuable natural resources, but also threatens the safety of human life and property, so the prevention and control of forest fires is of great significance. At this stage, the technology for forest fire monitoring is very mature, but there is a lack of systematic research on the prediction of fire probability for the time being. Therefore, this paper provides a study of forest fire prognosis by comprehensively analyzing multi-source remote sensing data and natural factor data. Firstly, this paper begins with an overview of the types of multi-source remote sensing data and their applications in forest fire research, including optical remote sensing, thermal infrared remote sensing, radar remote sensing, and LiDAR data. These data provide critical information for fire risk area identification, fire behavior simulation, and post-disaster assessment. Secondly, this paper analyzes the influence of natural factors such as vegetation characteristics, topography and soil conditions, and climatic conditions on the occurrence and spread of forest fires. Further, this paper explores the application of multi-source data in fire risk assessment, behavioral analysis and simulation, and post-disaster assessment and recovery planning, and demonstrates the potential of UAV remote sensing data in fire monitoring through a case study. Finally, this paper summarizes the research findings, discusses the advantages and limitations of the forest fire prediction methods based on multi-source data, and proposes suggestions for future research directions. This study expects to provide a scientific basis for forest fire prevention and response and to contribute to the sustainable management of forest resources and ecological environmental protection.

Keywords: Forest Fires; Multi-Source Data; Remote Sensing Technology; Fire Risk Assessment.

1. Introduction

Forests are one of the most biologically diverse ecosystems on Earth and have a critical impact on human productive life, biodiversity and global climate change [1]. Forest fires not only lead to a huge loss of forest resources, but also release large amounts of greenhouse gases into the atmosphere, exacerbating global warming [2]. Therefore, strengthening the prevention and management of forest fires and improving the emergency response capacity of forest fires are of great significance to the protection of forest resources, the maintenance of ecological balance and the promotion of sustainable development. Taking the occurrence of forest fires in 2014 given by the National Bureau of Statistics of China (Table 1) as an example, it can be seen that the scale of fire areas in various regions of China throughout the year is large, and the casualties and economic losses are serious. According to the China Forestry Statistical Yearbook, the number of fires during 2014 alone was 3703 [3], and the problem of preventing the occurrence of forest fires should not be underestimated.

Traditional forest fire monitoring and prediction methods mainly rely on manual patrols and ground observations, which are inefficient and difficult to cover large areas. Geographic Information System (GIS) and remote sensing play a vital role in the study of forest fires. Some studies have shown that it is possible to monitor fire incidents through changes in radiance and to provide fire management decisions by integrating meteorological satellite data [4]. In addition, UAV multispectral remote sensing technology has higher accuracy in monitoring and tracking forest fire conditions compared to visible light cameras [5]. However, there is limited research in China on predicting the probability of forest fires. Therefore, how to efficiently and accurately predict the occurrence probability of forest fires is an important breakthrough in the prevention and control of forest fires. In addition to the application of remote sensing technology in predicting the occurrence of forest fires, the investigation, statistics and analysis of other factors that trigger the occurrence of fires should be increased in order to better predict the occurrence of forest fires.

The aim of this study is to explore the forest fire prediction method based on multi-source data by comprehensively analyzing remote sensing data and natural factor data. The research includes the integration and analysis of multi-source remote sensing data, the establishment of fire risk assessment models, the simulation and prediction of fire behavior, and the development of post-disaster assessment and recovery planning. This paper will first present the application of multi-source remote sensing data in forest fire research, covering optical, thermal infrared, radar and LiDAR data to obtain information on ground cover, temperature anomalies and forest structure. Next, the effects of natural factors such as vegetation, topography, soil and climate on fire are analyzed. Further, to explore the application of these data in fire risk assessment, behavioral simulation, and post-disaster recovery planning, and to demonstrate the potential of UAV remote sensing technology in fire monitoring through case studies. It is expected that this research will provide a scientific basis for forest fire prevention and response and contribute to the sustainable management of forest resources and ecological environmental protection.

Table 1. Forest Fires in Some Parts of China (2014)

Region	Destructed Forest Area (hectare)	Natural Forest	Artificial Forest	Casualties (person)	Economic Loss (ten thousand yuan)
Total	19110	3710	12537	112	42512.8
Beijing	1		1		
Inner Mongolia	3426	2742	496	1	418.2
Liaoning	378	65	292	1	378.0
Zhejiang	786		395	9	
Fujian	1145	114	1031	2	33773.7
Jiangxi	1579	81	1499	4	1401.5
Henan	334		334	4	18.4
Hunan	1935	5	1930	5	369.4
Guangdong	930	23	907	14	189.8
Guangxi	1241	8	1233	10	854.5
Sichuan	766	347	419	3	1113.8
Guizhou	488	82	406	7	253.7
Yunnan	4236	51	2078	34	3112.2

2. Overview of Multiple Sources of Data

2.1. Multi-Source Remote Sensing Data

Multi-source remote sensing data types play a key role in forest fire prognostic studies by providing diverse information sources that contribute to a more comprehensive understanding and monitoring of forest fires. Multi-source remote sensing data types include optical remote sensing data, thermal infrared remote sensing data, radar remote sensing data, and LiDAR data.

2.1.1. Optical Remote Sensing Data.

Optical remote sensing data have a high spatial resolution and can provide detailed information on ground cover and vegetation conditions. Commonly used optical remote sensing satellites include Landsat, Sentinel series, etc., which are capable of providing multi-spectral and high-resolution images, which are helpful for the identification of fire risk areas and the assessment of damages after fires have occurred.

2.1.2. Thermal Infrared Data.

Thermal infrared data detect temperature anomalies primarily by measuring thermal radiation emitted from the surface. Such data are critical for real-time monitoring of the occurrence and spread of fires, as they can reveal small changes in surface temperatures, allowing for the rapid identification of potential fire hot spots.

2.1.3. LiDAR Data.

Laser radar (LiDAR) acquires highly accurate three-dimensional spatial data by transmitting laser pulses and measuring the timing of the return signal. LiDAR data can provide a detailed description of the vertical structure of the forest, including the height, density, and distribution of trees, which is useful for understanding the propagation mechanisms of forest fires and for assessing the impact of fires on forest structure.

2.2. Natural factors data

2.2.1. Vegetation characterization data.

The quantity of vegetation combustible materials and the dry-to-fresh ratio of combustibles can serve as important bases for forest fire prediction. Understory shrubs and herbaceous vegetation are typically classified as less flammable due to their low dry-to-fresh weight ratio. In contrast, the dry freshness of the understory litter is relatively high and is in a flammable state. The combustible content of stands of different age classes also varies. For example, the combustible loading of the tree layer and the understory litter layer gradually increased with increasing age. The combustible load in the shrub layer is greatest in the young forest period, while the combustible load in the herb layer is least in the young forest period [6]. Depending on the type of forest, the higher number of fires occurred in shrub forests, cedar forests, mixed forests, and piñon-juniper forests [7].

2.2.2. Topographic and soil condition data.

Steep slopes tend to lead to rapid flame spread, with heat and flames moving up the slope and accelerating the expansion of the fire, while gentle slopes help to slow down the spread of the fire. Slope aspects with longer sunlight exposure tend to have drier vegetation and higher flammability. Due to the influence of altitude, as elevation increases, temperatures usually decrease and humidity may increase, which could lead to vegetation at higher altitudes being less flammable.

Fires may last longer if the soil contains large amounts of underground combustible materials such as grass roots and tree roots. This is because these substances can be used as fuel during a fire. In addition, the chemical content of the soil also affects the probability of fire, for example, high effective phosphorus content in the soil can increase the combustibility of vegetation [8].

2.2.3. Climatic conditions data.

In hot environments, moisture in the air evaporates more quickly, making the relative humidity of the atmosphere lower, and the moisture in combustible materials decreases rapidly, thus increasing the risk of a fire. At the same time, a certain amount of heat is required for combustible materials to reach the ignition point, and the acquisition of this heat is highly related to the temperature of the surrounding air. In addition, once a fire occurs, the high temperature environment accelerates the spread of the fire [9].

Forest fire incidence was significantly and negatively correlated with the intensity and duration of precipitation. The time interval of precipitation also indirectly affects fire occurrence. When the interval is long, combustible materials dry out and easily start a fire. The study by Govender et al. noted that the total amount of combustible material increased with increased precipitation, which further increased the risk level of forest fires. In other words, when there is an increase in precipitation, there is an increase in the accumulation of combustible materials in the forest, which makes the fire danger of the forest rise [10].

3. Application of multi-source data in forest fire prognosis

3.1. Fire Risk Assessment and Surveillance

Vegetation indices, surface temperature and humidity data, which are indicators for assessing forest fire risk, can be performed on a large scale based on remote sensing. By analyzing these indicators, potential high-risk areas can be identified, enabling early warning for forest fires. Vegetation growth is assessed by calculating the difference between the reflectance in the infrared and visible bands through vegetation indices (e.g., NDVI), which is also an important indicator for assessing the health of vegetation, and combustible loads. In addition, surface temperature information can be obtained from thermal infrared remote sensing data, which can help to identify areas of high temperatures that may be fire initiation points or areas where fires have already occurred. Soil moisture is monitored by microwave remote sensing, and low soil moisture may lead to increased fire risk, while indirectly affecting vegetation moisture or reflecting surrounding air moisture.

3.2. Fire Behavior Analysis and Simulations

The use of multi-source remote sensing data, such as high-resolution satellite imagery, can provide a detailed view of the fire area, which can be used to identify the point of origin of the fire, the path of spread, the extent of the burn and the vegetation affected. Radar remote sensing technology has the advantage of penetrating clouds and smoke, even at night and even in bad weather conditions to obtain ground information and monitor fire conditions. The use of remote sensing data combined with topographical factors such as slope, direction, elevation, etc., as well as information such as wind direction and speed can be used to predict the direction of fire spread and more accurately simulate the path of fire propagation. These data help predict potential fire behavior and provide decision support for fire emergency response and resource allocation.

3.3. Post-disaster assessment and recovery planning

In the aftermath of a fire, remotely sensed data can provide a rapid assessment of the affected area, providing detailed information on vegetation damage, soil erosion and other environmental impacts. It is essential for developing effective restoration plans and monitoring the ecosystem's recovery process. For example, based on Sentinel-2 images to extract the ecological index of fire-burned sites and make an evaluation of vegetation restoration [11]. Comparison of satellite imagery before and after fires makes it possible to assess the direct damage caused by fires to forest ecosystems, including the area burned, the type of vegetation, and so on. The statistics and calculations of the loss of forest resources enable the assessment of the damage caused by fire to the forest economy [12].

4. Case Studies

4.1. Prediction of forest fires from UAV remote sensing data

Unmanned Aerial Vehicles (UAVs) show great potential for application in the field of forest fire monitoring and prevention. They are capable of efficiently monitoring a wide range of factors that can trigger forest fires. Ground information collected by UAVs, such as Digital Orthophoto Map (DOM) and Digital Surface Model (DSM) data, combined with the processing power of advanced software such as Pix4Dmapper, produces accurate topographic maps. These topographic maps provide important geographic information for forest fire risk assessment [13].

Airborne laser radar (LiDAR) systems are often equipped on UAVs and are capable of covering large areas and acquiring critical terrain data and vegetation information. These data are critical for analyzing potential fire hazard areas in forests such as steep slopes and valleys. With its excellent recognition capability, UAV-LiDAR technology is able to accurately estimate forest cover, tree height, tree species distribution, and biomass [14], which provides reliable data support for the development of forest fire prevention strategies.

In addition, the UAVs can carry a variety of weather sensors to monitor key weather parameters in the forest in real-time, such as temperature, humidity, barometric pressure, and wind speed, which are critical for predicting the likelihood of fires and assessing the rate and direction of fire spread. Equipped with a hyperspectral infrared imager, such as the X20P-IR, the UAV is able to detect thermal anomalies on the ground and spot potential spontaneous combustion points or small ignition sources in time. Combined with high-resolution cameras and spectral analysis technology, UAVs can assess the dryness and moisture content of vegetation, providing a powerful technical tool for early detection and rapid response to forest fires.

4.2. Prediction of forest fires by natural factors

Long Tengteng et al. showed that the spread of forest fires is closely related to factors such as the type of vegetation, climatic conditions, topographic features, and the distribution density of inhabitants. Among them, climatic conditions have the most significant effect on the spread of forest fires [15], so climatic factors can also be used as an important factor in predicting the occurrence of forest fires. Based on the forest fire incident data in China between 2011 and 2020, Lu Yi et al. selected climatic elements such as average annual barometric pressure, air temperature, precipitation, and hours of sunshine as the characteristic variables, and predicted the prediction of forest fire danger in each region of China through linear regression analysis [16]. Moreover, based on the comparison of the actual forest fire situation, it is proved that the linear regression line equation verifies the reliability of the cluster analysis method. As shown in Figure 1, the difference between the predicted and actual values is small, and the prediction error can be as low as 10,000th of a percentile in some areas.

In their study, researchers such as Sun Xuexia took a holistic approach to understanding the patterns and influencing factors of forest fires [17]. They conducted an exhaustive collection of actual fire points recorded between 2005 and 2018 and used mathematical and statistical methods to analyze the historical fire data in depth. In addition, they explored the correlations between these fires and 14 key factors that may influence forest fires and further investigated these relationships through statistical analysis. The results of the study showed that the number of fire points is higher in areas with high vegetation cover, which is significantly affected by the distribution of vegetation and the water content of combustible materials, so the forest stand factor is used as one of the important factors to analyze the data on the probability of forest fires.

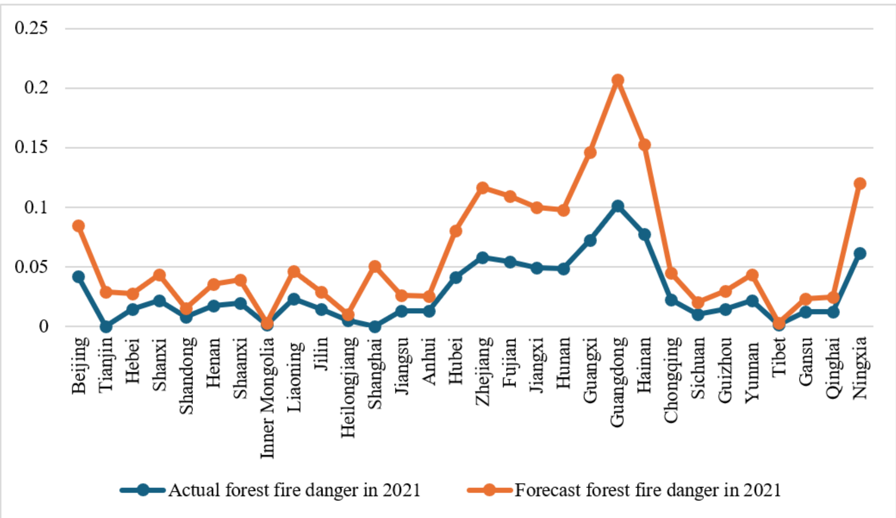

Figure 1. Comparison of real and predicted forest fire risk in 2021

5. Summary

Forest fire forecasting is researched in this paper by synthesizing and analyzing multi-source remote sensing data and natural factors data. The results show that multi-source data integration has significant advantages in improving the accuracy and real-time performance of forest fire risk assessment. Optical remote sensing data provided high-resolution ground cover information. Thermal infrared data effectively monitored temperature anomalies and radar and LiDAR data accurately characterized forest structure and topography. The integrated application of these data provides important support for the identification of fire risk areas, simulation of fire behavior, and post-disaster assessment. In addition, data on natural factors, including vegetation characteristics, topography and soil conditions, and climatic conditions, play a key role in understanding the mechanisms of forest fire occurrence and spread. Through case studies, this paper demonstrates the potential of UAV remote sensing data in real-time monitoring and assessment of forest fires, and the importance of natural factor data in fire prognosis.

Despite the progress made in forest fire prognosis in this study, there are still some limitations. For example, data integration and analysis methods need to be further optimized to improve the generalization ability and real-time response speed of the prediction models. In addition, the adaptability to different regions and different fire types needs to be further investigated.

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