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Application Of Spatio-Temporal Remote Sensing Data Analysis in Fire Monitoring

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Abstract. This paper investigates the application of spatio-temporal remote sensing data analysis in fire monitoring, aiming to cope with the increase in the frequency of forest fires and its threat to the ecological environment and human security due to global warming and increased human activities. The study describes the application of various remote sensing techniques in fire monitoring, including Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data, infrared remote sensing, satellite hyperspectral data, and SAR techniques. The application of remote sensing data in actual fire monitoring was demonstrated through case studies of the "330 forest fire" in Muli County, Sichuan Province, and the boreal forest fire in Canada. The integration of multi-source satellite remote sensing data can improve the timeliness of monitoring and avoid the interference of complex environments, thus reducing disaster losses. This paper argues that remote sensing technology has a broad development prospect in forest fire monitoring and that the accuracy and timeliness of monitoring can be improved by further integrating GIS, innovative technologies, and algorithmic applications. The future challenge lies in strengthening the integration of remote sensing technology and GIS to enhance data processing capability and disaster prediction accuracy to provide more effective support and assurance.

Keywords: Forest fire; remote sensing; fire monitoring.

1. Introduction

Fire is one of the natural disasters that cause major economic losses and ecological damage worldwide. With the aggravation of climate change and the increase of human activities, the frequency and intensity of fires show an upward trend, which brings great challenges to society and the environment. As an important part of fire prevention and control, the accuracy and timeliness of fire monitoring directly affect the efficiency and effectiveness of disaster relief. It is thus clear that early warning and effective fire monitoring are key to protecting lives and property. Spatial and temporal remote sensing data analysis, a powerful technological tool, can play an important role in fire monitoring and emergency response.

Traditional fire monitoring methods mainly rely on ground observation and manual reporting. Although the methods can provide certain information, there are problems such as limited monitoring range and slow response speed, which make it difficult to meet the needs of large-scale and fast-developing fire monitoring. With the development of remote sensing technology, the application of spatio-temporal data analysis in fire monitoring has gradually become a research hot spot. Remote sensing technology, through a variety of means such as satellites, drones, and ground sensors, can acquire fire data on a large scale and at a high frequency, providing a wealth of spatial and temporal information. The use of these data for spatial and temporal analysis can not only improve the accuracy and efficiency of fire monitoring but also provide a scientific basis for fire early warning, prevention, and control. Hilker et al [1] proposed a Spatial Temporal Adaptive Fusion Modeling algorithm for mapping Reflectance Change (STA-ARCH) to detect change points from dense time series of low-resolution imagery to improve the STARFM performance during land cover type change for sudden surface reflectance perturbation event scenarios. Huang et al. [2] utilized the STARFM algorithm and the temporal and spatial fusion algorithm of surface reflectance based on the time-phase change model of the components in the ground and jointly used a variety of better spatial resolution (≤30m) sensor images (Landsat8 OLI, Sentinel-2, GF-1 WFV) and MODIS images, to obtain a more accurate day-by-day medium spatial resolution prediction image [3], to support the monitoring of forest fire evolution and disaster damage assessment. The predictive images provide strong support for monitoring the evolution of forest fires and assessing the damage.

This paper will analyze the application of MODIS satellite data, infrared remote sensing data, hyperspectral remote sensing data, and SAR remote sensing data in fire monitoring, and specifically describe the specific cases of the "330 forest fire" in Muli County, Sichuan Province, and the boreal forest fire in Canada. A comprehensive assessment of these cases will help to reveal the practical application effects and potential challenges of remote sensing data analysis in fire monitoring, providing references and insights for future research.

2. Materials and Methods

2.1. Application of MODIS Satellite Data in Fire Monitoring

MODIS is a key NASA sensor aboard the Terra and Aqua satellites that has provided a large amount of Earth observation data since 2000. Its multispectral resolution allows it to probe the physical properties of the Earth's surface in 36 different bands, covering from the visible to the far infrared, which makes it possible to obtain detailed information about the Earth's surface and atmosphere. The spatial resolution of MODIS is 250 m (for some bands), 500 m and 1,000 m. The Terra and Aqua satellites provide global coverage at least once a day, which makes MODIS data well suited for monitoring fast-changing Earth phenomena, especially for fires. The specific applications of MODIS data in fire monitoring mainly include fire point detection, fire dynamic monitoring and fire impact assessment. For example, Liu et al [4] carried out fire monitoring using MODIS satellite data to quickly identify potential fire points by monitoring fire hotspots. They compared and analyzed the surface temperature and hotspot distribution in the study area with historical data on fire occurrence to achieve real-time fire monitoring and early warning. MODIS satellite data are characterized by a high frequency of observation in large-scale fire monitoring, which ensures the timeliness of fire monitoring. However, the medium spatial resolution limits the ability to detect small-scale fires.

2.2. Application of Infrared Remote Sensing Data in Fire Spread Prediction

Infrared remote sensing is an important means of obtaining physical and chemical information about the Earth's surface and atmosphere. It utilizes information on infrared radiation emitted, reflected, and transmitted by objects to detect the characteristics of the Earth's surface and atmosphere. Infrared remote sensing data are characterized by all-weather observation, high sensitivity, and real-time monitoring. Infrared remote sensing allows observations to be made during the day and at night, as well as under cloudy conditions, independent of light conditions. Infrared sensors detect subtle changes in surface temperature, sensitively capturing fire spots and high temperature areas. Many infrared remote sensing platforms can provide high-frequency data updates to support real-time monitoring and dynamic analysis of fire conditions [5].

The application of infrared remote sensing data in fire spread prediction mainly includes fire point identification, temperature anomaly monitoring, combustion intensity assessment, and fire spread model construction. For example, the direction and speed of fire spread can be predicted by analyzing the change of surface temperature, to establish the mathematical model of fire spread and then simulate the fire spreading process. And the infrared remote sensing data acquired in real time helps in model validation and adjustment [6]. However, infrared remote sensing data also have some limitations. Compared with visible remote sensing, infrared remote sensing usually has lower spatial resolution. Infrared remote sensing data require complex pre-processing and correction, and the analysis and application process are technically demanding.

2.3. Application of Hyperspectral Remote Sensing Data to Fire Smoke Monitoring

Hyperspectral remote sensing technology is a remote sensing technology that can provide continuous, narrow-band spectral information, which has unique application advantages in fire smoke monitoring [7]. The application of hyperspectral remote sensing data in fire smoke monitoring mainly includes smoke composition analysis, smoke concentration monitoring and constructing smoke dispersion model. Hyperspectral remote sensing data can be used to analyze the chemical composition of smoke, such as aerosols, carbonaceous particles, and water vapor. Spectral disaggregation techniques make it possible to identify and quantify the different components of smog, which is essential for understanding the impact of smog on the environment and human health. Hyperspectral remote sensing data can capture the subtle spectral features of smog, which allows quantitative assessment of the concentration and distribution of smog. Combined with hyperspectral data and other meteorological data, smoke dispersion models can be developed to predict the path of smoke propagation and future trends, providing a scientific basis for emergency management. The intensity and spatial distribution of fire smoke can be effectively monitored using satellite hyperspectral data. Quantitative monitoring and assessment of fire smoke can be achieved by analyzing hyperspectral data in different bands and identifying the characteristic spectra of fire smoke. In addition, the combination of meteorological data and geographic information system (GIS) data enables the simulation and prediction of the spreading path of fire smoke.

2.4. Application of SAR Remote Sensing Data in Fire Monitoring

SAR also plays a vital role in fire monitoring, as it can penetrate interference such as clouds and smoke, and can obtain surface information under adverse weather conditions, which is essential for discovering the location and spread of fires. Moreover, SAR data is not restricted by light conditions and can be used for all-weather, all-time monitoring, which is conducive to the timely tracking of fires. The higher ground resolution enables it to capture small changes in the surface, such as fire-induced hot spots and hot patches, which helps to accurately locate fires. Even small deformations of the ground surface can be monitored, including changes in vegetation structure and surface settlement [8], when combined with time-series data, can reveal fire-induced changes in the ground surface. In addition, SAR data can be used to extract temperature information and burning intensity in the burning area, which helps to assess the fire development situation and smoke spreading range and helps to predict the direction of fire development.

3. Case Studies

3.1. "330 Forest Fire" in Muli County, Sichuan Province

Rao et al. [9] utilized multi-source satellite remote sensing data to jointly monitor the "330 forest fire" area in Muli County, Sichuan. Firstly, the advantages of high spatial and temporal resolution and a mid-infrared fire-sensitive band of Gaofen-4 were fully utilized to determine the time and location of the fire by combining the time series changes of the smoke screen, temperature, and vegetation index. Next, Sentinel-2 data were used to monitor the spectral information of different burned areas. Next, dNBR (differenced Normalized Burn Ratio) was extracted using Sentinel-2 data, and a step-by-step method based on the maximum interclass variance algorithm (OTSU) was proposed to determine the traces and areas of different degrees of fire burning. Finally, the relationship between Sentinel-1A Polarization Ratio (PR) and NDVI is established to compensate for the observation limitations of optical data during cloud interference. Utilizing the advantages of Sentinel-2 spatial and spectral resolution, the combination of dNBR and OTSU algorithms can step-by-step determine the areas with different degrees of fire and can accurately extract the fire areas.

Figure 1 shows the change of Sentinel-1A data after the first fire in the fire area, which is represented by the increase of polarization ratio from 6.6 dB (March 22) to 10.8 dB (April 3), and the weakening of depolarization effect reflects the reduction of vegetation. Figure 2 shows the NDVI map simulated by Sentinel-1A data on April 3, and the NDVI of the fire area was lower than that of the healthy woodland in the same week. SAR data as complementary data to NDVI in fire monitoring during severe weather in the region improves the temporal resolution of forest fire monitoring. Based on the location of the fire point, the time of fire initiation (March 30) was determined due to the decrease in NDVI during the spread of the fire (from 0.7 to 0.25); there were differences in spectra in the range of 490-2200 nm between the fire area and the unaffected area, as well as between different types of fire trails. The joint use of multiple types of satellites to monitor forest fires can improve the temporal resolution of monitoring. The error tolerance of the monitoring method will be further improved, and the purpose of monitoring forest fires in small areas of China with high spatial resolution and full spectral range will eventually be realized.

Utilizing the characteristics of Sentinel-2 with many data bands and combining the actual survey data for different kinds of fire traces spectral comparison, we provide spectral information support for short-term extraction and classification of fire traces. However, the spectral resolution of the multispectral sensors carried by Sentinel-2 is still too low, and if there is airborne hyperspectral data for fire observation, more spectral analysis information can be provided for forest fire.

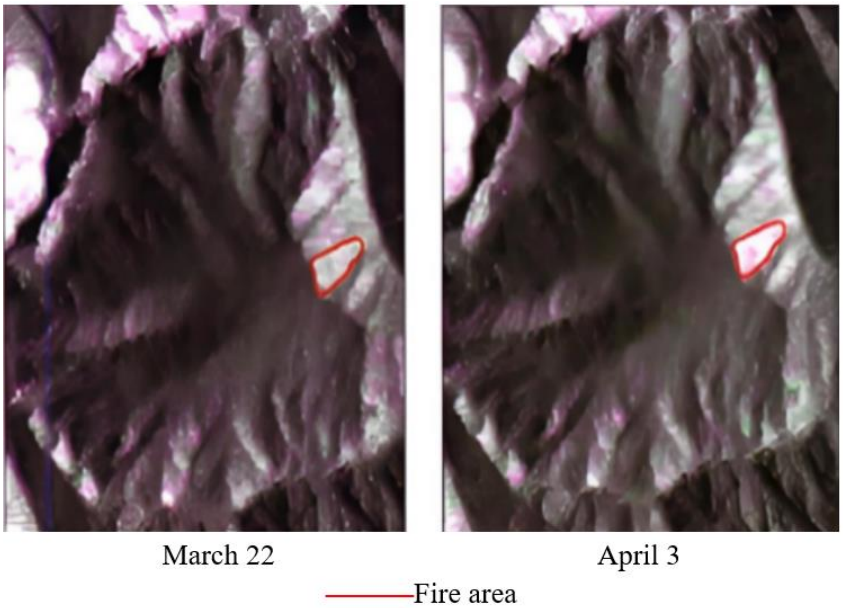

Figure 1. Changes in Sentinel-1A data before and after the first fire [9]

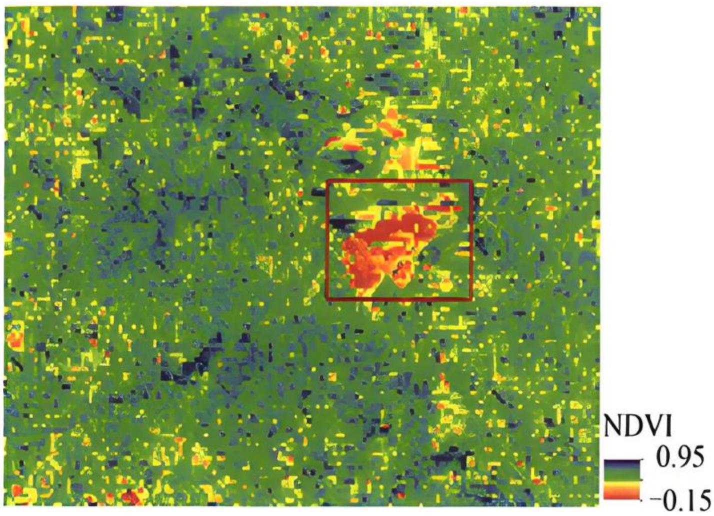

Figure 2. Simulated NDVI map based on April 3 SAR data [9]

3.2. Boreal Forest Fires in Canada

The study area is in the Canadian boreal forest-covered provinces of Saskatchewan and Alberta. You Hui and other scholars [10] used MODIS EVI data and LST data from 2003 to 2011, as well as the Global Disturbance Index (MGDI) method, to detect the forest fire disturbance conditions in the major forest fire areas in Canada from 2004 to 2011. The results were compared with MODIS standardized fire-scarred land products and Canadian Forest Service statistics. At the same time, the inter-annual variation and spatial distribution of the area of burned land in the study area were analyzed. First, based on satellite remote sensing data, shapefiles or raster data of the hill fire boundaries and affected areas were acquired. Second, data related to the intensity and distribution of smoke can be obtained to show the degree of burning and smoke propagation of the hill fire. Next, data preprocessing is performed on multiple remote sensing data sources. Combining data from multiple sources helps to obtain more comprehensive information, and image preprocessing ensures that the data accurately reflects surface characteristics and the accuracy of the analysis results. Remote sensing data are then used to estimate the size of hill fires and thus assess the extent of fire spread. Potential fire hotspots in remote sensing images are detected to enable rapid response and control of fire spread. By observing the trajectory of smoke propagation, we can then analyze the impact of fire on the environment and human health.

The results of the annual fire trails detected from 2004 to 2011 were superimposed to generate a multi-year fire trail distribution map. The main locations of forest fires are the boreal reserve, the coniferous reserve, and the northeastern part of the northern plains. In Saskatchewan and Alberta's 2004-2011 forest fire trail detection results, fire reduced 11.00% (468,300 hm^2) and 1.63% (295,300 hm^2) of the province's total forest area, respectively, with Saskatchewan burning almost 1.6 times as much forest as Alberta. Among them, 2006, 2008, 2010, and 2011 were the main years of forest fires in the study area, with an average reduction of the forest area of 1,198,300 hm^2 per year. Except for 2011, Sa'ada province was the main province in the study area where fire trails occurred. The locations where forest fire trails occur are concentrated in the Boreal Preserve, Conifer Preserve, and Conifer Plains areas of the Ecological Intertwine Zone, as well as the Wood Buffalo National Forest Preserve in the northeastern portion of the Boreal Plains.

The disturbance index algorithm uses MODIS data with a spatial resolution of 1000m, thus some small and relatively weak fire trails cannot be detected. The algorithm is good at detecting fires larger than 10km^2. This study did not consider the effect of vegetation restoration, and the areas of forest restoration can be extracted in future studies by setting the DI difference. In addition, due to the uncertainty of the MCD12Q1 surface classification product itself, it will cause some errors to its results.

4. Conclusion

With climate warming and increased human activities, the frequency of forest fires has increased, posing a threat to the environment and lives. To enhance early warning and monitoring of fires, spatial and temporal remote sensing technologies are widely used for fire monitoring and analysis. By utilizing the advantages of MODIS, which is efficient and accurate, the real-time status of fires can be monitored, and infrared, hyperspectral, and SAR technologies also play an important role. This paper reveals the practical application of remote sensing in monitoring through the case studies of the "330 forest fire" in Muli County, Sichuan Province, and the boreal forest fire in Canada. The integration of multi-source satellite remote sensing data can improve the timeliness of monitoring. The use of remote sensing data to analyze smoke, hot spots, and fire extensions, combined with GIS analysis, can help in spatial pattern recognition and in predicting the direction of mountain fires. Remote sensing technology has a broad development prospect in forest fire monitoring.

Through continuous innovation and application, monitoring accuracy and timeliness can be improved and disaster losses can be effectively reduced. Using spatio-temporal remote sensing data analysis, combined with different sensor images and algorithms, more accurate fire monitoring, evolution tracking, and disaster assessment can be realized. In the future, the integration of remote sensing technology and geographic information systems should be strengthened to improve data processing capacity and disaster prediction accuracy and to provide more effective support for forest fire monitoring, prevention, and control.

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