A Review on Remote Sensing Applications for Wildfires Studies

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ABSTRACT

Wildfires are among the most prominent disturbances in forest and grassland ecosystems during different seasons and is considered as a natural hazard and become a threat to property, human life, and the economy. Annually around 350 to 450 million hectares of forests burn globally which is releasing 1.5 to 3 petagrams of carbon and other components that negatively impact the atmosphere. This review examines the use of remote sensing technologies to study wildfires across different regions. The mega Amazon rainforest generates over 20% of earth's oxygen but has surprisingly shifted from carbon sink to carbon emitter due to frequent wildfire patterns. Spatio-temporal analysis, forest density estimation, and hot spot analysis, are significant for observing regional variations in wildfire patterns. Monitoring large area become cost-and-time effective by using Satellite imagery. They provide periodic scenarios and multiple approaches to help monitor and analyze factors that affect forest fires. A wide range of fire detection sensors like Moderate Resolution Imaging Spectroradiometer (MODIS), Visible Infrared Imaging Radiometer Suite (VIIRS) and Sentinel with various indices such as normalized burned ratio (NBR), burned area index (BAI), normalized burned thermal ratio (NBTR) and have widely employed by researchers in recent past. Significant (growth has been noticed in wildfires occurrence via remote sensing, which is driven by advancements in detection methods and data acquisition. NOAA- AVHRR, Normalized Difference Vegetation Index (NDVI) and surface temperature images have been used for monitoring, experimental studies with microwave data and synergisms between spectral domain, such as combining microwave with optical or thermal infrared data show promising results in forest fire monitoring. However further investigation is required to develop operational multi-sensor system that are both effective and economically viable.

1. Introduction

Forest contribute to the terrestrial carbon sink and play significant role in regulating carbon cycle. Forest fires management is an important practice to manage natural resources. Forest plays vital role in economy, tourism, and protection against natural hazards (Ghorbanzadeh *et al*., 2019). Wildfires are disastrous as they can result from lightning, or due to human errors, such as improperly discarded cigarettes. The continuous increase in atmospheric temperature and droughts make wildfires more intense and hazardous (National Geographic Society, n.d.). According to an estimate approximately 350 to 450 million hectares burn globally releasing 1.5 to 3 petagrams of carbon and other components annually. This huge amount of smoke impacts the quality of atmosphere (Leblon *et al*. 2016). Wildfires bring the abundant destruction in the forest and grassland ecosystems all around the world. It also has significant ecological benefits to the forest ecosystem in regulating plant succession and fuel accumulation. Sometimes, wildfires are regulated along with safety measures to maintain healthy vegetation and promote specific plant species that depend on fire for regeneration, which also prevents destructive wildfires (National Geographic Society, n.d.). Fire has played a crucial role in shaping ecosystems throughout history, influencing vegetation distribution and ecosystem functioning. While fire can be a natural ecological factor, uncontrolled and destructive wildfires pose a severe threat to many environments. Remote sensing has become a

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valuable tool for wildfire studies, offering satellite imagery to map fire perimeters, assess severity, and monitor vegetation changes over time. Early studies employed remote sensing by NOAA-AVHRR NDVI images to estimate LFMC, leveraging vegetation greenness as a proxy. Additionally, surface temperature data from NOAA-AVHRR were employed, either independently or in conjunction with NDVI, to enhance moisture assessments. However, these methods were limited by cloud cover, which reduces image availability (Leblon B *et al*., 2021).

Earth Observation Systems, such as Sentinel and Landsat, provide essential data for tracking land surface and vegetation dynamics. However, challenges such as cloud cover and limited temporal resolution can affect data accessibility and its quality. The growing interest in wildfire research has led to an increase in literature review, which used statistical methods to evaluate publication trends, key contributors, and thematic developments in the field. These analyses are helpful to identify research gaps and provide insights into evolving methodologies. While previous studies have reviewed wildfire and remote sensing research, a comprehensive analysis of global scientific literature over an extended period remains necessary (Singh *et al*., 2023).

Prime objectives of this review article include:

1. To review and compile latest literature on forest fire detection/monitoring system using satellite data.
2. To explore the usefulness of different satellite technologies for wildfire monitoring.

3. To evaluate the significance of modern geospatial techniques such as machine learning to identify hot spots of forest fire for rapid mitigation. Studies performed by Seydi (2025) revealed that Remote sensing technologies have significantly enhanced the ability to monitor and assess wildfire events, providing valuable insights into fire dynamics, environmental impacts, and human exposure. The beginning of this year January 2025, marked the history of destruction caused by a major wildfire event in Los Angeles County, California. High-resolution Sentinel-2 imagery played a crucial role in detecting burned areas and mapping land cover dynamics. The utilization of Chebyshev-Kolmogorov-Arnold network (Cheby-KAN) models enabled the accurate delineation of fire-affected regions with notable performance metrics, including a Kappa coefficient of 0.9714 and an overall accuracy of 98.68%. For a comprehensive impact assessment, the integration of remote sensing data with population, land use, and infrastructure databases allowed, revealing significant variations in demographic acquaintance, infra-structural damage, along with ecological vulnerability. Results showed that low height shrubland ecosystems were most susceptible to fire spread, while, urban-wildland interface zones experienced higher levels of structural damage. Furthermore, demographic analyses, utilizing WorldPop data, recognized the Palisades Fire as having the largest human impact so far, where, over 20,000 individuals were affected directly or indirectly. Thus, remote sensing technologies offer essential tools for improving wildfire risk assessments, response strategies, and post-fire recovery planning, especially in complex, urbanized fire-prone regions like Los Angeles.

The MODIS sensor, specifically the MCD14ML global monthly fire location product from NASA's Terra and Aqua satellites, was utilized in the study by Ma *et al.,* 2022 to detect wildfire occurrences across the Brazilian Amazônia Biome. This satellite-derived fire dataset, along with NDVI-based calculations for fractional vegetation cover, was integrated into a GIS framework, where a fishnet grid approach was employed for obtaining spatial aggregation and analysis. Advanced GIS techniques, including Kernel Density Estimation, Moran's I spatial

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autocorrelation, and hotspot analysis (using Getis-Ord Gi* and OHSA), were helped to map wildfire clusters and understand their spatial patterns. Eventually, the combination of remote sensing and GIS enabled detailed identification of wildfire hotspots and refined spatial regression modelling (via GWGR and GWPR), significantly enhancing the accuracy and interpretability of wildfire hazard assessments at the regional scale.

Table 1. Summary of selected literature relevant to major global wildfire events

Title of study	Affected Area/Damage Assessment	Reference
Monitoring post-wildfire vegetation response with remotely sensed time-series data in Spain, USA and Israel	USA, Israel, and Spain	Van Leeuwen *et al.*, 2010
Remote Sensing of Wildland Fire-Induced Risk Assessment at the Community Level	Wenchuan, China.	Ahmed, Rahaman, & Hassan, 2018
Remote sensing role in environmental stress analysis: East Serbia wildfires case study (2007-2017)	East Serbia	Potić *et al.*, 2017
The use of remote sensing in mapping and monitoring vegetation change associated with bushfire events in Eastern Australia	Eastern Australia	Milne A.K., 1986
Assessment of the January 2025 Los Angeles County wildfires: A multi-modal analysis of impact, response, and population exposure	Los Angeles, USA	Seydi, S. T. 2025
Characterizing Spatial Patterns of Amazon Rainforest Wildfires and Driving Factors by Using Remote Sensing and GIS Geospatial Technologies	Amazon biome, Brazil	Ma *et al*., 2022
Impact of California Fires on Local and Regional Air Quality: The Role of a Low-Cost Sensor Network and Satellite Observations	California	Gupta *et al*., 2018

Ahmed, Rahaman, & Hassan, (2018) had utilised high-resolution WorldView-2 satellite imagery for assessing structural damages caused by the Horse River Fire (HRF) in Fort McMurray in 2016. Apart from estimating structural damages, delineation of the Wildland-Urban Interface (WUI) and its buffer zones at varying distances were also computed to assess the fire risk areas. They have found a strong correlation ($r^2 = 0.97$) between ground-based data and satellite-based damage estimates. The analysis also revealed that vegetation within 10m to 30m buffers from the WUI added to fire vulnerability, with 30% of these areas deemed at risk. Vegetation removal within these zones was shown to be effective in mitigating fire risk. The study emphasizes the importance of planning, regular monitoring and vegetation management to reduce wildland fire-induced risks and protect communities of nearby areas.

The results of the research work of Gupta *et al.*, 2018 revealed, that wildfires in arid regions like California had a significant impact on air quality and human health. Satellite sensors such as NASA's Suomi NPP-VIIRS and Aqua-MODIS monitor aerosol optical depth (AOD), assisting in monitoring and assessing smoke plumes. However, translating AOD to near-surface PM2.5 concentrations involves assumptions about particle properties and meteorological conditions. Low-cost air quality monitors (LCAQMs), like the Purple Air PA-II sensor, offer real-time ground-level data. These devices correlate well with reference instruments, despite of some overestimation of PM2.5 levels. Integrating satellite AOD with LCAQM data not only increases spatial coverage and real-time monitoring but also improves air quality assessments during wildfire events. Differences between Satellite and surface measurements, including aerosol distribution and sensor biases challenges will remain in reconciling. More sustained research into calibration and data assimilation is vital for real-time air quality management during wildfire events.

The effectiveness of remote sensing techniques, mainly Landsat imagery, for monitoring the impacts of wildfires on land cover and ecosystems was demonstrated by Potić et al.

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(2017). Machine learning algorithms like Random Forest and spectral indices such as Normalized Burn Ratio (NBR) and its difference (ΔNBR), were utilized in the study, which later successfully classified land cover types and assessed wildfire severity and its impact. Both pre-and post-fire analyses revealed significant changes in land cover, where forests cover increasing, and pasture land was decreasing due to the wildfire. The classification accuracy was high (87.5-89.17%) while detailed change detection endorsed that remote sensing is a powerful tool for long-term environmental monitoring, wildfire detection, land cover analysis, and regardless of challenges in distinguishing certain land cover types like bare soil and pasture land.

Post-fire vegetation recovery in Spain, Israel, and the USA using MODIS NDVI data from 2000 to 2007 was performed by Van Leeuwn *et al.*, (2010) in their research findings it was revealed that only two sites experienced net vegetation increase while all other sites exhibited reduced landscape heterogeneity over time. This time-series phenological metrics specified changes in community composition, with some showing significant post-fire trends. Field validation confirmed NDVI's reliability, especially with low to moderate vegetation cover. The study underscores the utility of MODIS NDVI in monitoring post-fire dynamics and highlights the importance of integrating satellite data with ground observations for comprehensive ecosystem assessments. Moreover, climatic factors, notably droughts and temperature extremes, significantly influenced recovery trajectories.

The body of literature, Milne, A. K. (1986), on mapping fire occurrences using Landsat imagery emphasizes its pivotal role in post-fire analysis and vegetation monitoring despite inherent limitations for real-time fire tracking. Researchers have demonstrated that the orbital return periods of 16–18 days restrict the utility of Landsat for capturing rapid fire events—especially under conditions of intense smoke cover and variable fire fronts—the sensor's unique ability to record spectral reflectance provides a lasting record of fire events. This record enables detailed mapping of burn boundaries, assessment of fire severity, and monitoring of subsequent vegetation regeneration through techniques such as band rationing (notably between bands 7 and 5), supervised and unsupervised classifications, and principal component analysis. These methodologies reveal not only the spatial extent of fires but also nuances in burn intensity and regrowth dynamics, underscoring the value of Landsat data in integrating fire behaviour, fuel mapping, and ecological recovery into an extensive framework of landscape management and fire risk assessment.

1.1 Advanced technology and wildfire management

In the recent past, satellite imaging technology have significantly improved wildfire management and has enabled real-time monitoring, classification, and predictive modeling. High-resolution spectral data from ASTER and Hyperion satellites were geometrically corrected and processed using Principal Component Analysis (PCA) to enhance image quality for accurate vegetation classification. A supervised classification approach, utilizing field data and the Maximum Likelihood Algorithm, mapped vegetation types and densities, with additional noise reduction techniques improving reliability. The classified satellite data was then integrated into a fire propagation model, enhancing fire spread simulations and aiding in wildfire prediction based on vegetation characteristics. The integration of remote sensing, advanced image processing, and predictive modelling provides a powerful tool for wildfire management, enabling

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early detection and improved risk assessment (Keramitsoglou *et al.*, 2008).

Similarly, the TELEIOS and SWeFS wildfire monitoring service utilizes satellite images to improve wildfire management. It integrates fire-related satellite data with additional geospatial sources using Semantic Web technologies. By representing data in RDF and using ontologies, the system ensures seamless interoperability. Processed efficiently with Strabon, it provides real-time and archived hotspot data. These methods can also support wildfire prediction by incorporating weather, human activity, and regional flammability data (Kyzirakos *et al.*, 2014).

Moreover, the introduction of Distributed Satellite Systems (DSS) plays an important role in wildfire management by providing a responsive solution for real-time Earth Observation (EO). Using a constellation of Low Earth Orbit (LEO) satellites equipped with optical payloads, DSS enhances wildfire detection, monitoring, and response through continuous coverage and rapid data processing. Inter-satellite communication and intelligent DSS (i-DSS) capabilities allow satellites to track and image affected areas efficiently and assisting near real-time disaster response. By leveraging AI-based segmentation and onboard data processing, DSS further improves fire detection accuracy and minimizes delays in sensing wildfire hotspots, making it an essential tool for effective wildfire prediction, mitigation, and emergency response efforts (Thangavel *et al.*, 2023).

2. Materials and Methods

In this study, authors have reviewed relevant literature on wildfires assessment using remote sensing and GIS. Later on, identified the most relevant studies for a comprehensive review and comparison of seven research papers obtained from Google scholar, was made which mainly focus on wildfire monitoring and assessment using remote sensing techniques. These selected studies provide a valuable insight into various methodologies, including satellite-based monitoring, spectral analysis and numerous machine learning applications, spread prediction and post-fire impacts on vegetation and ecosystem. By synthesizing the findings from these papers, we identified challenges and advancement in remote sensing for wildfire analysis. This review paper may serve as a foundation for further research and analytical approaches and evaluation metrics for wildfire assessment.

The search was based on keywords such as wildfires assessment, geospatial data, major events regarding wildfires and factors associated with wildfire provocation, spatio-temporal, and time series, with an inclusion criterion.

3. Results and Discussion

The literature reviewed underscores the critical role of remote sensing in wildfire assessment, pre fire risk, active fire monitoring and post-fire recovery and alteration. The synthesis of these findings enlightened the need for advancement in satellite-based fire detection, damage caused, vegetation monitoring and air quality analysis, and most importantly inducing remote sensing technologies in mitigating wildfire-induced risks. The Effectiveness of high-resolution satellite imagery, such as Worldview-2 and sentinel-2 was studied by Ahmed *et al.*, (2018) and Seydi (2025). The decline of Wildland-Urban interface (WUI) or buffer zones revealed that vegetation within 10m-30m significantly increased fire vulnerability. The recent incident of Los Angeles Wildfires Chebyshev-Kolmogorov-Arnold networks (Cheby-KAN) attained 98.68% accuracy in signifying the potential of machine learning in wildfire impact assessments. Moreover, Van Leeuwn *et al.*, (2010) and Milne (1986) also confirmed the potential of the application of multi-temporal satellite data in monitoring vegetation cover change evident after

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wildfire. The use of MODIS NDVI from 2000-2007 revealed differences in post-fire vegetation recovery in the USA, Israel and Spain. The effect is mainly due to climatic conditions. Wildfires are significantly degrading the air quality of the respective area. The California Wildfire study demonstrated that aqua-MODIS sensors provide essential insight into aerosol optical depth (AOD) and low-cost air quality monitors (LCAQMs). To enhance the air quality monitoring, we need to calibrate the system to enhance real-time surface-level $PM_{2.5}$ estimations. The East Serbia study enhances the need for reliance on machine learning in Wildfire assessment. Utilization of spectral indices such as Normalized Burn Ratio and Random Forest classification for detecting burn severity and land cover transitions is also a popular method. The key findings of this review are that high resolution optical and multispectral satellites are highly effective, MODIS is crucial for post-fire vegetation monitoring, but lacks in real-time tracking. Machine learning enhances the impact assessment and risk severity mapping. Vegetation management in buffer zones is critical for fire risk mitigation, as the dense vegetation is correlated with devastating fire related damages.

As far as efficiency or comparison of satellites for fire detection is concerned, there are multiple RS data and techniques found helpful depending on the size of area and the purpose of monitoring. MODIS satellite with variable resolutions (1 and 2 Km) respectively, along with the thermal infrared band, which can sense heat even at night, is considered one of the best for the detection of forest fire at a large scale with high temporal resolution. Similarly, VIIRS performs the same function but with little sharper resolution of 375m, which can highlight small pockets of forest fire areas in both day and night. Moreover, when detailed mapping of burned areas for post fire damage assessment is required, so high resolution Sentiel-2 satellite data is ideally used due to its high resolution of 10 m. These days real-time monitoring of wildfires using thermal band and AI powered Drone is also common, which gives accurate results for early warning

4. Conclusion

After witnessing the Los Angeles wildfires incident this year in January, the State of Wildfires report 2025 declares that climate change has increased atmospheric temperatures and in some regions, triggered wildfires and increased vulnerability by up to 30 times. Advancements in satellite technology is truly proving as one of the best contributions for solving real-world problems faced by both developing and developed countries.

The use of satellite data is vital as it detects, monitors and tracks colossal areas of wildfire which may be shared with the stakeholders or authorities for public awareness, warnings, alerts and mitigation. Moreover, these medium and high-resolution images are helpful for post fire damage assessment, future planning and preparedness to avoid and deal with such disasters, hence, highly recommended for effective management of natural resources.

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