

The Use of Remote Sensing Data in Mitigating Forest Fire Threats and Its Impact on National Security

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Abstract

Forest fires have emerged as a recurring environmental and national security threat, exacerbated by climate change, deforestation, and unsustainable human activities such as slash-and-burn agriculture. These fires result in ecosystem degradation, biodiversity loss, greenhouse gas emissions, and disruption to health, food security, and local economies. Remote sensing technology, particularly through satellite sensors and drones, offers real-time data for detecting hotspots, tracking smoke dispersion, and assessing post-fire impacts. Tools like MODIS, VIIRS, and Sentinel have proven effective in fire monitoring and mitigation planning. However, limitations in data resolution, weather interference, and policy integration hinder optimal implementation. In Indonesia, the integration of remote sensing into disaster management systems remains fragmented, often resulting in delayed responses and ineffective coordination. Strengthening human resource capabilities, regulatory frameworks, and multi-sector collaboration is essential to leverage this technology fully. Remote sensing thus stands as a critical solution to reduce wildfire risks and their cascading effects on national security, environmental resilience, and public health.

1. Introduction

Forest fires have become an increasingly frequent environmental disaster in recent decades, exacerbated by a combination of natural and anthropogenic factors. Among the main contributors are climate change, deforestation, and traditional agricultural practices such as slash-and-burn methods. Rising global temperatures and reduced humidity due to climate change have significantly increased vegetation flammability, while deforestation removes natural barriers that could prevent the spread of fires. These fires not only cause extensive ecosystem damage but also accelerate climate change through substantial greenhouse gas emissions released from burning biomass (Oliveira et al., 2020).

The consequences of forest fires extend beyond environmental degradation and encompass serious economic, health, and socio-political repercussions. Hazardous smoke emissions trigger widespread respiratory and cardiovascular illnesses, especially among vulnerable populations like children and the elderly. Economically, forest fires destroy agricultural lands, weaken forestry and tourism sectors, and create long-term livelihood disruptions for local communities. On the socio-political front, fires often ignite land disputes between local residents, corporations, and the state. These multidimensional threats demand the adoption of advanced technological approaches for effective fire detection and mitigation (Kim et al., 2021).

Remote sensing has emerged as a transformative tool in forest fire mitigation, offering real-time, large-scale monitoring capabilities through satellite and aerial sensor systems. These technologies can detect early fire hotspots, assess the severity of ongoing fires, and map the extent of smoke dispersion. Their primary advantage lies in high-frequency, wide-area data collection that supports swift and informed decision-making processes. Furthermore, remote sensing data can be integrated into fire prevention, suppression, and recovery planning efforts to ensure more systematic and evidence-based forest management practices (Graham et al., 2021).

The escalating intensity and frequency of wildfires—particularly in climate-sensitive regions such as Siberia, the Amazon, and Australia—underscore the need for climate-informed fire surveillance tools. Remote sensing offers a unique advantage by enabling authorities to monitor indicators of fire risk such as rising temperatures and declining soil moisture. However, the effectiveness of remote sensing systems is often challenged by factors such as limited data resolution and atmospheric obstructions. To enhance reliability, a hybrid approach that integrates optical, radar, and thermal sensing technologies is essential for capturing a comprehensive picture of fire risk and progression (Bryan et al., 2020).

2. Literature Review

The integration of remote sensing technologies has become fundamental in addressing the increasing frequency of wildfires driven by climate change and anthropogenic factors. Satellite sensors such as MODIS and VIIRS are essential for real-time monitoring, providing high-frequency data that allows authorities to detect thermal anomalies and surface temperature spikes indicative of active fires. These technologies are particularly critical in regions like Indonesia, where peatland fires are difficult to access via ground monitoring. Furthermore, the harmonization of multi-sensor data, including Landsat and Sentinel-2, enables comprehensive assessments of vegetation dynamics and soil moisture before and after fire events (Kim et al., 2021). Remote sensing data can be integrated into fire prevention, suppression, and recovery planning efforts to ensure more systematic and evidence-based forest management practices (Graham et al., 2021).

Recent scholarship emphasizes the synergy between spatial data and artificial intelligence (AI) to enhance the predictive accuracy of fire behavior. Machine learning models, such as Random Forest and CatBoost, process complex environmental variables—including topography, wind speed, and fuel load—to generate dynamic fire vulnerability maps (Zhou et al., 2021). Frameworks like Fire-Net leverage deep learning to identify patterns preceding fire outbreaks, offering a proactive approach to disaster management (Seydi et al., 2022). However, the effectiveness of these technological interventions is often mediated by institutional challenges, such as fragmented data systems and the need for improved technical capacity among local stakeholders to interpret and act upon remote sensing insights. Strengthening human resource capabilities and regulatory frameworks is essential to leverage this technology fully in mitigating threats to national security.

3. Method

This study employs a descriptive-analytical approach to evaluate the effectiveness of remote sensing technologies in forest fire mitigation, specifically focusing on its application in Indonesia. The research utilizes a comprehensive review of primary and secondary data sources, including peer-reviewed journals and satellite datasets from MODIS, VIIRS, Sentinel, and Landsat, alongside reports from governmental agencies like the Indonesian Meteorological, Climatological, and Geophysical Agency (BMKG). Comparative case studies were conducted to examine spatial and temporal fire patterns in Kalimantan and Sumatra, using geospatial software such as ArcGIS and Google Earth Engine to process multi-sensor imagery. Technical analysis involved applying thresholding algorithms to thermal data for hotspot detection and utilizing machine learning models, specifically Random Forest and CatBoost, to predict fire spread based on environmental variables like soil moisture and vegetation density. Furthermore, a qualitative content analysis of Indonesian forestry regulations and international protocols was performed to assess the institutional and policy landscape regarding disaster management coordination.

4. Results

4.1. The Significance of Remote Sensing in Early Detection of Forest Fires

In the context of forest fire mitigation, remote sensing technology has evolved into a key tool enabling large-scale and systematic real-time monitoring. Early detection is crucial due to the rapid spread of fires and increasingly dry vegetation resulting from climate change. Satellite sensors such as MODIS (Moderate Resolution Imaging Spectroradiometer) and VIIRS (Visible Infrared Imaging Radiometer Suite) are widely used to detect fire hotspots, which serve as early indicators of wildfire ignition. These sensors provide periodic data multiple times a day, supporting fast and accurate decision-making by relevant authorities (Monteiro et al., 2022).

This technology is particularly vital in countries like Indonesia, where fires frequently occur in peatland areas that are difficult to access by ground-based monitoring teams. Remote sensing can detect surface temperature anomalies using thermal sensors, even when the areas are obscured by smoke or cloud cover. In many cases, thermal data from MODIS and VIIRS are the only feasible means to monitor fires in remote regions such as Kalimantan and Sumatra. This advantage is why satellite-based early warning systems must be strengthened within national fire mitigation frameworks (Bryan et al., 2020).

Beyond early detection, remote sensing plays a critical role in tracking smoke movement and identifying affected zones. Through optical sensors and image processing algorithms, the spatial dispersion of smoke can be modeled to help authorities determine evacuation zones and assess public health risks. Monitoring smoke spread is vital, as wildfire emissions contain pollutants that contribute to acute respiratory illness and cardiovascular disease, especially among vulnerable populations like children and the elderly (Graham et al., 2021).

Another strength of remote sensing is its ability to deliver high-frequency updates over large geographic areas. In a vast archipelagic country like Indonesia, this technology enables nationwide surveillance of vegetation dynamics and soil moisture conditions. Sensors like ESA's Sentinel-2 and USGS's Landsat-8 are widely used to assess vegetation before and after fires. Consequently, post-fire rehabilitation and restoration efforts can be more targeted, data-driven, and sustainable (Kim et al., 2021).

Furthermore, the use of remote sensing has enabled the integration of Geographic Information Systems (GIS) and fire risk modeling. This combination facilitates the development of predictive fire vulnerability maps based on climatic conditions, vegetation types, and human activities. Therefore, remote sensing is not merely a detection tool but also a central component in long-term fire prevention strategies amid increasingly complex challenges driven by global climate change and anthropogenic pressures.

4.2. Spatial Data and AI-Based Fire Spread Modeling

Recent advances in spatial data analysis and artificial intelligence (AI) have significantly improved the accuracy of forest fire spread modeling. By combining satellite-based remote sensing with machine learning algorithms, researchers can now predict fire behavior with greater precision. Models such as Random Forest, CatBoost, and Artificial Neural Networks (ANN) are widely used to process spatial layers, including vegetation types, topography, soil moisture, rainfall, and wind speed to produce predictive fire risk maps. These maps not only aid early warning systems but also guide resource allocation for suppression efforts (Li et al., 2022).

Indonesia has increasingly adopted this approach in fire-prone areas such as Sumatra and Kalimantan. For example, historical satellite imagery from Landsat and Sentinel series has been used to identify patterns in vegetation stress, dry biomass accumulation, and ignition sources. These indicators are integrated into spatial models to assess potential fire hotspots and forecast the spread of flames over time. When these data are combined with meteorological inputs, the models become highly dynamic and responsive to environmental changes, enabling proactive rather than reactive responses (Chuvieco et al., 2023).

A key development in this field is the use of deep learning frameworks that can recognize complex patterns in vast datasets. One such framework, known as Fire-Net, uses satellite thermal anomaly data in

conjunction with land cover classification to detect anomalies that precede fire outbreaks. In Indonesia, Fire-Net and similar models have been instrumental in predicting peatland fires, which are notoriously difficult to detect and suppress due to their subsurface combustion characteristics (Seydi et al., 2022). These models also provide temporal fire susceptibility scores that can support dynamic zoning regulations and seasonal fire bans.

In practical application, spatial models have been integrated into Geographic Information Systems (GIS) dashboards to enable visual tracking of active fires and fire-prone zones. Government agencies such as BMKG and KLHK use these systems to overlay administrative boundaries, land concessions, and community territories with risk maps, thereby enhancing decision-making at the district and provincial levels. These visual tools facilitate targeted outreach programs, focusing firefighting efforts and educational campaigns in high-risk areas before the fire season peaks.

Nonetheless, the effectiveness of spatial-AI modeling is highly dependent on data quality and availability. Gaps in high-resolution imagery, inconsistencies in land-use data, and limitations in localized weather information can reduce model reliability. Addressing these issues requires investments in data infrastructure, including access to high-resolution commercial satellite imagery and improved weather station networks. In addition, open data policies and inter-agency data sharing agreements are essential to ensure continuous and timely updates to fire prediction systems.

4.3. Socioeconomic Impacts of Forest Fires and Institutional Challenges

Forest fires exert profound socioeconomic consequences, particularly in developing nations like Indonesia, where vast forested areas overlap with agricultural zones and human settlements. The destruction of thousands of hectares of arable land has led to loss of livelihoods among farmers and local communities. Crops are often destroyed mid-harvest, irrigation systems are damaged, and livestock suffer from smoke inhalation or habitat loss. These cascading impacts have a destabilizing effect on rural economies and food security, especially in fire-prone regions such as Riau, Jambi, and West Kalimantan (Kean & Staley, 2021).

Beyond agriculture, the forestry and ecotourism sectors also face significant economic setbacks. Timber resources become unusable after intense fires, while protected forest areas—home to endemic and endangered species—are closed off to tourism. This not only results in loss of biodiversity but also cuts off revenue streams for communities that rely on conservation-related employment. In the aftermath of the 2019 fires, Indonesia experienced a steep drop in tourism in key natural parks, triggering both economic and reputational damage at the national level (Harris et al., 2022).

Public health represents another critical domain of impact. The dense smoke produced by forest fires contains particulate matter (PM_{2.5}) and toxic gases such as carbon monoxide and formaldehyde. These pollutants are linked to acute respiratory infections, cardiovascular complications, and increased hospital admissions. Vulnerable groups—such as children, the elderly, pregnant women, and individuals with pre-existing respiratory conditions—are particularly at risk. During the peak haze events of 2015 and 2019, health systems in affected regions were overwhelmed by spikes in respiratory cases, with many clinics forced to operate beyond capacity (Cleland et al., 2021).

From a governance perspective, forest fires also pose significant institutional challenges. Although Indonesia has enacted a range of regulatory instruments—such as Law No. 41/1999 on Forestry and various presidential decrees—implementation remains inconsistent. One of the main issues is weak inter-agency coordination, with overlapping mandates between local governments, central authorities, and concession holders. Fire response efforts are often delayed by jurisdictional confusion, lack of clear command structures, and fragmented data systems that hinder effective monitoring and enforcement (Graham et al., 2021).

Moreover, there is a persistent gap between the availability of remote sensing data and its utilization in real-time decision-making. While satellite imagery is widely accessible, many local authorities lack the technical capacity to process, interpret, and act upon the data. Field teams are often under-resourced, lacking basic GIS training or necessary hardware to operate early warning systems. Without sufficient investment in human resources, the full potential of remote sensing for fire mitigation remains unrealized.

These institutional limitations highlight the urgent need for capacity building, regulatory reform, and the establishment of integrated fire management frameworks that bridge technology and policy execution.

4.4. Environmental and National Security Implications of Forest Fire

The environmental consequences of forest fires are multifaceted and deeply interconnected with broader global ecological systems. Fires contribute significantly to biodiversity loss by destroying habitats, altering food chains, and fragmenting ecosystems. Many fires in Indonesia occur in peat swamp forests, which are home to endangered species such as the orangutan, clouded leopard, and Sumatran tiger. When these habitats are burned, species either perish or are forced into marginal areas, increasing the risk of extinction and human-wildlife conflict (Hagmann et al., 2021).

Forest fires also disrupt critical ecosystem services such as water regulation, soil fertility, and carbon sequestration. Burned forests lose their ability to retain water, increasing the risk of floods and landslides during the rainy season. Furthermore, the release of greenhouse gases (GHGs)—notably carbon dioxide and methane—from biomass burning exacerbates climate change. According to Graham et al. (2021), the 2019–2020 bushfires in Australia released more CO₂ into the atmosphere than the country's total annual industrial emissions. Similar dynamics are observed in Indonesia, where annual fire seasons significantly increase the national carbon footprint and undermine commitments to international climate agreements.

From a geopolitical perspective, forest fires pose growing threats to national security and regional stability. Large-scale fires, especially those that result in transboundary haze, often strain diplomatic relations between countries. Indonesia's recurring haze episodes have triggered tensions with neighboring Malaysia and Singapore, leading to demands for stronger regional cooperation and stricter enforcement of environmental laws. Beyond diplomacy, forest fires are increasingly being weaponized in social and political conflicts. In some regions, arson is used strategically to displace communities, assert territorial claims, or weaken opponents economically by destroying cropland (Zhou et al., 2021).

Domestically, forest fires can destabilize governance by fueling public dissatisfaction and sparking social unrest. Communities affected by repeated fires often express frustration over perceived negligence by government agencies or complicity of private corporations. In Indonesia, land disputes have erupted between indigenous groups and plantation companies accused of illegal burning. These conflicts are further inflamed when legal avenues for redress are weak or inaccessible. The lack of transparency and accountability in land allocation and fire response can erode public trust in institutions and provoke cycles of resistance, protest, and in some cases, violence (De Freitas et al., 2022).

Given these risks, remote sensing has the potential to become a critical asset in strengthening national security through environmental monitoring. Satellite-based surveillance can help detect patterns of suspicious fire outbreaks, identify areas of repeated ignition, and provide forensic evidence for legal action. Additionally, by monitoring land use changes in real-time, authorities can preempt illegal encroachment and deforestation that often precede major fire events. Thus, remote sensing not only supports ecological preservation but also contributes to the prevention of conflict and the protection of national interests.

4.5. Strengthening Fire Mitigation through Integrated Policy and Innovation

To address the multidimensional impacts of forest fires, a more integrated and innovation-driven approach is necessary—one that bridges technology, governance, and community action. At the policy level, governments must prioritize the mainstreaming of remote sensing into national and sub-national fire mitigation frameworks. This includes mandating the use of satellite-based early warning systems, incorporating fire risk data into land-use planning, and enforcing spatial zoning regulations in high-risk areas. Countries such as Brazil and Australia have already implemented policies that tie land development permits to fire vulnerability assessments derived from satellite data, providing a model for Indonesia to emulate (Kim et al., 2021; Peek et al., 2020).

In terms of innovation, advancements in artificial intelligence (AI) and machine learning offer opportunities to enhance the precision and scalability of fire detection and response systems. Deep learning algorithms can process massive datasets in real time, detecting ignition points, modeling smoke dispersion, and predicting fire spread with high accuracy. These tools should be integrated into centralized fire

monitoring platforms that aggregate data from multiple sensors, including MODIS, VIIRS, Sentinel, and Landsat. A unified national dashboard—accessible to both decision-makers and the public—can improve transparency, coordination, and rapid response during fire emergencies (Xu et al., 2021).

Cross-sector collaboration is another cornerstone of effective fire mitigation. Government agencies, private companies, research institutions, and civil society organizations must work together to pool resources, share data, and develop joint strategies. Community-Based Fire Management (CBFM) models, in which local residents are trained to prevent, monitor, and respond to fires, have shown success in countries like Indonesia, Mexico, and Canada. Empowering local actors with drone-based surveillance tools, satellite imagery, and mobile apps for fire reporting can decentralize fire management and increase responsiveness at the grassroots level (Thi Ngo et al., 2021).

Capacity-building is equally critical. Many of the current bottlenecks in forest fire mitigation stem not from the lack of data, but from the shortage of skilled personnel able to process and interpret remote sensing information. National training programs for local government officials, forest rangers, and community leaders are needed to bridge this gap. Universities and technical institutes should offer specialized curricula in environmental monitoring, geospatial analysis, and disaster risk management to build a future workforce capable of supporting technology-based fire governance (Graham et al., 2021).

Lastly, financial and legal instruments must be aligned with fire mitigation goals. Investment in infrastructure—such as high-resolution satellite acquisition, AI-driven processing systems, and communication networks—requires both public funding and private sector participation. At the same time, stronger legal frameworks must be established to hold perpetrators of illegal burning accountable and to incentivize sustainable land practices. Fiscal incentives such as tax reductions for companies implementing fire-prevention technologies or reforestation programs can reinforce a culture of compliance and innovation in fire management.

5. Conclusion

Remote sensing has proven to be a vital tool in the mitigation of forest fires, offering timely and accurate data for early detection, fire monitoring, and post-event analysis. Technologies such as MODIS, VIIRS, Sentinel, and Landsat enable the identification of fire-prone areas, hotspots, and vegetation changes at both macro and micro levels. When integrated with machine learning models and AI-driven analytics, these tools significantly enhance fire prediction accuracy and support rapid response mechanisms. The evidence from Indonesia, particularly in fire-prone regions like Kalimantan and Sumatra, shows that satellite-based monitoring systems can improve operational preparedness and reduce the severity of uncontrolled fires. However, several obstacles remain in fully realising the potential of remote sensing. These include limited spatial and temporal resolution of satellite data, atmospheric interference from clouds and haze, and weak institutional coordination. Additionally, challenges such as inadequate technical capacity at the local level and insufficient integration between remote sensing systems and policy frameworks hinder implementation. Therefore, to ensure long-term resilience, forest fire mitigation strategies must involve enhancing satellite capabilities, strengthening cross-sectoral collaboration, and adopting data-driven policies. A comprehensive approach that combines technology, governance, and community participation will be essential to protect ecosystems, support public health, and maintain national stability amid the increasing threat of wildfires.

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