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Review

Advances in Forest Fire Detection, Prediction and Behavior: A Comprehensive Survey

[1]Ahmad Alkhatib and [2]Khalid Jaber

[1]Department of Cyber Security, Al-Zaytoonah University of Jordan, Airport St, Amman, Jordan
[2]Department of Computer Science, Al-Zaytoonah University of Jordan, Airport St, Amman, Jordan

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Corresponding Author:
Ahmad Alkhatib
Department of Cyber Security, Al-Zaytoonah University of Jordan, Airport St, Amman, Jordan
Email: ahmad.alkhatib@zuj.edu.jo

Abstract: Forest fires are a major environmental challenge that poses a threat to both human life and ecological health. To effectively prevent and manage forest fires, it is crucial to have reliable detection, prediction and behavior analysis systems in place. This study provides a comprehensive survey of the different approaches and techniques used for forest fire detection, prediction and behavior analysis. It covers ground-based and aerial surveillance systems, remote sensing technologies, machine learning-based approaches and social media-based systems. The paper also discusses the challenges and limitations of current systems and provides insights into future directions for research and development in this field. Overall, this study highlights the importance of leveraging multiple data sources and analysis methods to improve our understanding of forest fire behavior and develop effective strategies for managing this environmental threat.

Keywords: Forest Fire, Detection, Prediction, Behavior Analysis, Ground-Based Systems, Aerial Surveillance, Remote Sensing, Machine Learning, Social Media, Early Warning, Risk Assessment, Fire Management

Introduction

Forest fires are a serious threat to the environment, wildlife and human lives around the world. Early detection, accurate prediction and effective management of forest fires are crucial to minimizing their impact. In recent years, advances in technology and machine learning have provided new opportunities for improving forest fire detection, prediction and behavior analysis. There are various methods and technologies available for forest fire detection, including ground-based systems, aerial surveillance and remote sensing techniques. One new contribution to forest fire detection is the use of machine learning algorithms and satellite data to identify and track potential wildfires. By analyzing changes in vegetation and thermal anomalies in satellite imagery, machine-learning algorithms can detect and classify potential fires with high accuracy (Jain *et al*., 2020). Furthermore, the use of drones equipped with thermal cameras and sensors can also aid in the detection of forest fires. These drones can quickly and efficiently survey large areas of forest and identify areas of high heat or smoke (Guimarães *et al*., 2020).

In addition to these technological advancements, community involvement is also crucial in detecting forest fires. Citizen reporting and monitoring systems, such as the Firewatch app (Planet, 2016), can help individuals report potential fires and receive alerts about nearby fires in real time.

Overall, the integration of machine learning algorithms, satellite data, drones, WSN, IOT and community involvement in forest fire detection can significantly improve the speed and accuracy of identifying and preventing forest fires. Here is a brief summary of some of the current methods.

Forest Fire Detection Techniques

Over the years numerous have been developed to detect forest fires, ranging from ground-based systems to aerial surveillance methods. The following techniques are used for detecting forest fires as shown in Fig. 1:

- Ground-based systems: Ground-based systems include fixed and mobile sensors that can detect smoke, heat and other indicators of fire. Examples include infrared cameras, flame detectors and thermal sensors These systems are relatively inexpensive and can provide real-time data, but they are limited by their range and require a network of sensors to cover large areas (Ambrosia and Wegener, 2009; Ryu and Kwak, 2022)
- Aerial surveillance: Aerial surveillance involves

using drones or aircraft to monitor forests and detect signs of fire. This method can cover a larger area than ground-based systems and can provide high-resolution imagery. However, it requires specialized equipment and trained personnel to operate and the imagery must be analyzed in real time (Daud *et al*., 2022; Mehmood *et al*., 2022)

- Remote sensing: Remote sensing involves using satellites and other remote sensors to detect heat and smoke from forest fires. This method can cover large areas and is particularly useful in detecting fires in remote or inaccessible regions. However, it can be expensive and is limited by cloud cover and other environmental factors (Santos *et al*., 2021; Dennison *et al*., 2014)
- Machine learning-based approaches: Machine learning-based approaches involve training algorithms to detect forest fires using data from sensors or satellite imagery. These methods can improve the accuracy and speed of detection and can be applied to various types of data. However, they require large amounts of training data and can be limited by the quality of the input data (Sathishkumar *et al*., 2023; Zhang *et al*., 2016)
- Social media-based approaches: Social media-based approaches involve using social media platforms to detect and monitor forest fires. These methods rely on crowdsourced data and can provide real-time information about the location and severity of fires. However, they are limited by the availability and reliability of social media data (Slavkovikj *et al*., 2014)

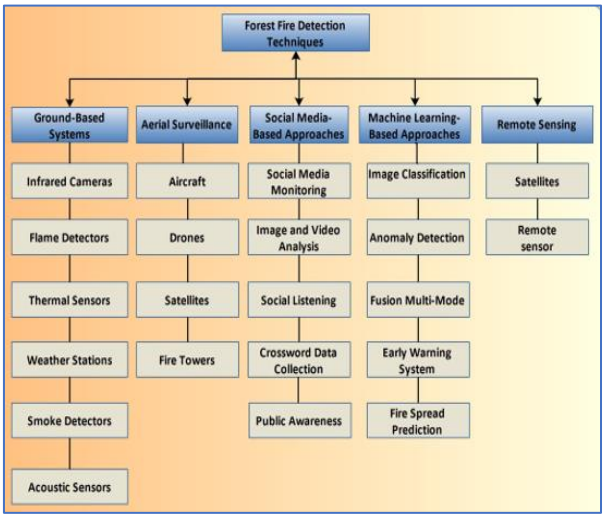

Fig. 1: Forest fire detection techniques

Forest Fire Prediction Techniques

Forest fire prediction techniques aim to identify the likelihood of a fire occurring in a particular area and estimate its potential size and behavior. Below are some of the common techniques used for predicting forest fires as shown in Fig. 2:

- Historical data analysis: Historical data analysis involves analyzing past forest fire data to identify patterns and trends that can help predict future fires. This can include data on fire frequency, location, size and behavior. Statistical models can be used to analyze this data and predict the likelihood of future fires based on environmental factors such as temperature, humidity and precipitation (Alkhatib and Abed-Al, 2022; San-Miguel-Ayanz *et al*., 2019; Chuvieco *et al*., 2010)
- Remote sensing: Remote sensing involves using satellite imagery and other remote sensing technologies to detect changes in vegetation moisture and other environmental factors that can increase the risk of forest fires. These changes can be used to predict the likelihood of a fire occurring in a particular area and estimate its potential size and behavior (Chuvieco *et al*., 2010)
- Weather monitoring: Weather monitoring involves tracking weather conditions such as temperature, humidity, wind direction speed and precipitation. This information can be used to predict the likelihood of a fire occurring and estimate its potential behavior (Cohen, 2000)
- Machine learning: Machine-learning techniques involve training algorithms to identify patterns and trends in data that can help predict future forest fires. This can include data on weather conditions, vegetation moisture and other environmental factors. Machine learning algorithms can be used to analyze this data and develop models that can predict the likelihood of a fire occurring in a particular area (Rakshit *et al*., 2021)
- Social media analysis: Social media platforms can be used to identify trends and patterns that may be indicative of a forest fire. For example, an increase in posts about smoke or flames in a particular area could signal the start of a fire. Machine learning algorithms can be used to analyze this data and provide early warning alerts to emergency responders (Boulton *et al*., 2016)

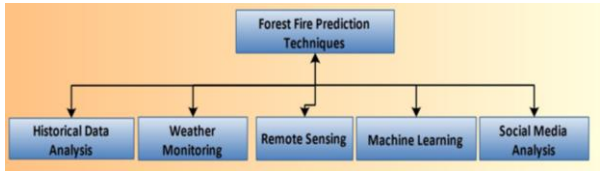

Fig. 2: Forest fire prediction techniques

Overall, forest fire prediction techniques rely on a combination of data sources and analysis methods to provide a comprehensive understanding of the risk of forest fires. By combining these techniques, fire managers can develop effective strategies for preventing and managing forest fires.

Forest Fire Behaviour Analysis Techniques

Forest fire behavior analysis techniques are used to understand and predict the behavior of a forest fire, including its rate of spread, direction, intensity and likelihood of ignition. Here are some common techniques used for forest fire behavior analysis as shown in Fig. 3.

- Fire behavior modeling: This technique involves using mathematical models to simulate the spread and behavior of a fire. Models can take into account factors such as topography, fuel characteristics and weather conditions to predict fire behavior (Kucuk and Sevinc, 2023; Alkhatib, 2013)
- Fire behavior assessment: This technique involves direct observation and analysis of a fire to assess its behavior. Firefighters and fire behavior analysts use visual cues such as flame length, smoke color and wind direction to assess the fire's behavior and predict its spread (Andrews, 1986)
- Fuel mapping: This technique involves creating detailed maps of the types and distribution of fuels in an area to predict the potential behavior of a fire. By understanding the types and densities of fuels, analysts can predict how quickly a fire will spread and how intense it will be (Scott, 2005; Heisig *et al*., 2022)
- Weather monitoring: Weather conditions such as temperature, wind speed and humidity can greatly impact fire behavior. By monitoring weather conditions in real-time, fire behavior analysts can adjust their predictions and provide more accurate information to firefighters and other emergency responders (Miyanishi, 2001; Cohen, 2000)
- Remote sensing: This technique involves using satellites or other remote sensing technologies to gather data on forest fires. This can include information on the location, size and behavior of the fire, which can be used to create more accurate fire behavior models and predictions (Chuvieco *et al*., 2010)

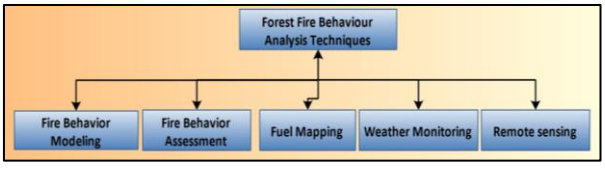

Fig. 3: Forest fire behavior analysis techniques

Overall, understanding the behavior of a forest fire is crucial for firefighting and emergency response efforts. By using a combination of techniques like those listed above, analysts can provide valuable information to firefighters and emergency responders to help them contain and control the fire as quickly and safely as possible.

Ground-Based Techniques Used for Forest Fire Detection

Ground-based systems are one of the methods used for forest fire detection. These systems typically use a network of sensors, cameras, or other instruments placed on the ground to detect smoke, heat, or other indicators of a forest fire. Here are some of the most common types of ground-based systems used for forest fire detection:

- Infrared cameras: Infrared cameras are devices that detect infrared radiation, which is emitted by objects based on their temperature. These cameras can detect heat signatures from wildfires and can be used to monitor fires at night when visibility is limited (Ambrosia and Wegener, 2009)

Examples of ground-based systems used for forest fire detection that incorporate infrared cameras:

– Fire watch: Fire watch is a ground-based system that uses infrared cameras to detect forest fires. The system is equipped with multiple sensors, including infrared cameras, to provide a 360°-view of the surrounding area. The system uses algorithms to analyze the thermal images captured by the infrared cameras and identify potential fire hotspots (IQ-FireWatch, 2023) FLIR aerial firefighting system: The FLIR aerial firefighting system is a ground-based system that uses infrared cameras to detect forest fires from a distance. The system includes a thermal imaging camera mounted on a telescoping mast, which can be raised to a height of up to 30 feet. The camera can detect temperature differences as small as 0.1° Celsius, allowing it to detect fires before they become visible to the naked eye (Georgiades *et al*., 2019)
– DRS technologies tamarisk: The DRS technologies tamarisk system is a portable ground-based system that uses infrared cameras to detect forest fires. The system includes a thermal imaging camera mounted on a tripod, which can be easily transported and set up in the field. The camera can detect hotspots as small as 0.5 square meters, allowing it to quickly detect and locate fires (Jeong and Kim, 2020)

- Flame detectors: Flame detectors use optical sensors to detect the light emitted by flames. These detectors can be used to detect fires at their early stages when the flames are small and may not be visible to the naked eye (Basu *et al*., 2018)

Examples of ground-based systems used for forest fire detection that incorporate flame detectors:

- Wasp wildfire detection system: The wasp wildfire detection system is a ground-based system that uses a combination of flame detectors and infrared sensors to detect forest fires. The system is mounted on a telescoping mast and can be used to monitor large areas. The flame detectors can detect the unique signature of a forest fire and alert firefighters to the presence of a fire (WASP, 2020)
- Fire sentry FS24X flame detector: The fire sentry FS24X flame detector is a portable ground-based system that uses a sophisticated infrared sensor to detect forest fires. The system can detect fires from up to 200 feet away and can be easily transported and set up in the field. The flame detector can distinguish between real fires and false alarms caused by things like sunlight, headlights and other heat sources (Lisakov *et al*., 2015)
- Viper perimeter protection system: The viper perimeter protection system is a ground-based system that uses a combination of flame detectors, infrared sensors and video cameras to detect forest fires. The system is designed to monitor large areas and can be integrated with other sensors and alarms to provide comprehensive wildfire detection and protection (Viper perimeter protection system, 2023)

- Thermal sensors: Thermal sensors detect changes in temperature and can be used to detect heat signatures from wildfires. These sensors can be installed on towers or other structures and can be connected to a central monitoring system

Examples of ground-based systems used for forest fire detection that incorporate thermal sensors:

- AlertWildfire: AlertWildfire is a ground-based system that uses thermal sensors to detect forest fires. The system is made up of a network of cameras equipped with thermal sensors that can detect heat signatures associated with forest fires. The cameras are strategically placed in areas prone to wildfire and are connected to a central monitoring system that can alert firefighters and other emergency responders in real time (AlertWildfire, 2024)
- ThermEye: ThermEye is a portable ground-based system that uses thermal sensors to detect forest fires. The system is designed to be quickly deployed in the field and can be used to monitor large areas. The sensors are mounted on a tripod and can detect temperature differences as small as 0.1° Celsius, allowing it to detect fires before they become visible to the naked eye

- Weather stations: Weather stations can be used to monitor weather conditions that can contribute to the spread of wildfires. They can measure temperature, humidity, wind speed and other environmental factors that can affect the behavior of fires. Examples of ground-based systems used for forest fire detection that incorporate weather stations:

- Campbell Scientific Weather Station: The Campbell Scientific Weather Station is a ground-based system that incorporates a weather station for forest fire detection. The system is equipped with sensors that can detect temperature, humidity, wind speed and other weather variables that can affect the likelihood of a forest fire. The data from the weather station can be used to inform fire management decisions and help predict fire behavior (Campbell Scientific, 2024)
- Wildfire watcher: Wildfire watcher is a ground-based system that uses a network of weather stations to monitor weather conditions that can lead to forest fires. The system collects data on temperature, humidity, wind speed and other variables and uses this data to predict the likelihood of a forest fire. The data can also be used to inform fire management decisions and help prevent forest fires from occurring (PreventionWeb, 2021)
- Fire weather intelligence portal: The fire weather intelligence portal is a ground-based system that incorporates a weather station for forest fire detection. The system collects data on temperature, humidity, wind speed and other variables and uses this data to create fire weather forecasts. The forecasts can help inform fire management decisions and provide advance warning of weather conditions that could lead to a forest fire (NC Climate Blog, 2023)

- Smoke detectors: Smoke detectors are sensors that can detect the presence of smoke and other particulate matter in the air. They can be used to detect forest fires by monitoring the concentration of smoke in the air.

Examples of ground-based systems used for forest fire detection that incorporate smoke detectors:

- Smoked system offers a comprehensive solution for effective smoke detection in various environments, particularly in forested areas prone to wildfires. Through advanced technology and innovative design, Smoked System provides a reliable means of early detection, crucial for preventing and managing forest fires. The system integrates multiple smoke detectors strategically positioned across the landscape, ensuring comprehensive coverage and timely detection of smoke signatures associated with wildfires. Leveraging real-time data processing capabilities, Smoked System promptly alerts

firefighting teams and emergency responders upon detecting potential fire outbreaks, facilitating swift intervention to mitigate the spread of fires and minimize damage to natural ecosystems and surrounding communities. With its robust and proactive approach to fire detection and management, Smoked System stands as a vital tool in safeguarding forests and preventing catastrophic wildfire events (Smoked System, 2010). Fireguard smoke detection system: The fire guard smoke detection system is a portable ground-based system that uses smoke detectors to detect forest fires. The system can be easily transported and set up in the field and is designed to monitor large areas. The smoke detectors are connected to a central monitoring system that can alert firefighters and other emergency responders in real-time (Krüll *et al*., 2012)

- VESDA smoke detection system: The VESDA smoke detection system is a ground-based system that uses advanced smoke detection technology to detect forest fires. The system is equipped with multiple smoke detectors that are sensitive enough to detect smoke particles in the air, even before a fire is visible. The system can be integrated with other sensors and alarms to provide comprehensive wildfire detection and protection (VESDA, 2023)

- Acoustic sensors: Acoustic sensors can detect the sound of wildfires, which can help locate fires in dense forest areas. These sensors can be used to detect the characteristic sounds of wildfires, such as crackling and popping sounds

Examples of ground-based systems used for forest fire detection that incorporate acoustic sensors:

- RASS: Radio Acoustic Sounding System (RASS) is a ground-based system that uses acoustic sensors to detect forest fires. The system is made up of multiple acoustic sensors that can detect the distinct sound of a forest fire, including the sound of crackling flames and falling debris. The system is connected to a central monitoring system that can alert firefighters and other first responders in real time (Sahin and Ince, 2009)
- Fire watch: Fire watch is a ground-based system that uses a combination of thermal and acoustic sensors to detect forest fires. The acoustic sensors can detect the sound of a forest fire and the thermal sensors can detect the heat signature of a fire. The system uses advanced algorithms to analyze the data collected by the sensors and identify potential fire hotspots
- DASH: Detection and Alert System for High-risk wildfires (DASH) is a ground-based system that uses acoustic sensors to detect forest fires. The system is equipped with multiple sensors that can detect the sound of a forest fire and can differentiate between the sound of a forest fire and other sources of noise. The system is designed to be quickly deployed in the field and can be used to monitor large areas (Wildfire Defense Systems, 2021)

Ground-based systems are useful for detecting and monitoring forest fires in localized areas, such as campgrounds, residential neighborhoods, or areas close to roads. However, they may not be practical for large-scale monitoring of remote forest areas due to their limited range. A combination of ground-based systems and other methods such as aerial surveillance and remote sensing may provide the most effective solution for forest fire detection and prevention. Ground-based systems can also be used for forest fire prevention, in addition to detection. Here are some examples of how ground-based systems are used for forest fire prevention (National Park Service, 2024; USDA, 2019; National Interagency Fire Center, 1973; US Department of the Interior, 2018):

- Firebreaks: Firebreaks are strips of land cleared of flammable materials, such as trees, shrubs and grass. Firebreaks create a barrier between the fire and the surrounding vegetation, which can help to slow or stop the spread of the fire. Ground-based equipment such as bulldozers and excavators are used to create firebreaks
- Prescribed burning: Prescribed burning is a technique used to reduce the fuel load in forested areas by intentionally setting fires under controlled conditions. This can be done using ground-based equipment such as drip torches or flamethrowers. Prescribed burning can help to reduce the risk of uncontrolled wildfires by reducing the amount of fuel available to burn
- Fuel management: Fuel management involves removing dead and dry vegetation from forested areas to reduce the risk of wildfires. Ground-based equipment such as mowers, chainsaws and chippers can be used to clear vegetation and create fuel breaks
- Fire suppression: Ground-based equipment such as fire engines and water tenders are used to suppress fires once they have been detected. Firefighters use hoses, pumps and other equipment to extinguish fires and prevent them from spreading
- Education and outreach: Ground-based systems can also be used for education and outreach to prevent wildfires. Public education campaigns can help to raise awareness about the causes of wildfires and teach people how to prevent them. Ground-based systems such as signage and trail markers can be used to inform visitors about fire danger levels and fire restrictions

Aerial Surveillance Techniques Used for Forest Fire Detection

Aerial surveillance is an important method for detecting forest fires, especially in remote or hard-to-reach areas. Aerial surveillance involves the use of aircraft, drones, or other airborne platforms to scan large areas of forest for signs of smoke or fire. Here are some examples of how aerial surveillance is used for forest fire detection (Yuan *et al*., 2017):

- Aircraft: Fixed-wing aircraft and helicopters equipped with cameras, infrared sensors and other instruments can be used to detect smoke and other indicators of forest fires. Pilots can fly over remote areas and use high-resolution cameras to detect smoke plumes or fire hotspots. Infrared sensors can also detect heat signatures from wildfires
- Drones: Drones or Unmanned Aerial Vehicles (UAVs) can be used for forest fire detection and monitoring. Drones can be equipped with cameras, thermal sensors and other instruments to detect smoke and heat signatures. They can also be used to map the location and extent of a fire and monitor its progression

Examples of aerial surveillance systems used for forest fire detection that incorporate drones:

- DJI Mavic 2 enterprise dual: The DJI Mavic 2 enterprise dual is a small drone equipped with both visual and thermal cameras. The thermal camera can detect the heat signature of a forest fire, even through smoke or in low-light conditions, while the visual camera can provide additional situational awareness. The drone can be quickly deployed and can cover large areas, making it a useful tool for detecting and monitoring forest fires (DJI, 2024)
- Lockheed Martin INDAGO: The Lockheed Martin INDAGO is a small drone equipped with an electro-optical and infrared (EO/IR) camera that can detect the heat signature of a forest fire. The drone is designed to be rugged and weather-resistant, making it well-suited for use in challenging environments. The drone can be used to monitor forested areas and provide early warning of potential fires (Lockheed Martin, 2021)
- Insitu ScanEagle: The Insitu ScanEagle is a larger drone equipped with a thermal camera that can detect the heat signature of a forest fire. The drone is designed to be launched from a catapult and can stay aloft for up to 24 h, making it a useful tool for monitoring large areas. The drone can be operated remotely and can transmit real-time video and data back to a command center (Insitu, 2005)

These are just a few examples of aerial surveillance systems that incorporate drones for forest fire detection. Drones are useful for monitoring forested areas and can provide early warning of potential fires, allowing firefighters and other first responders to respond quickly and effectively.

- Satellites: Satellites equipped with sensors that can detect changes in temperature, reflectance and other indicators of forest fires can be used for forest fire detection. These sensors can detect the heat emitted by fires, the smoke plumes and the changes in vegetation that can occur as a result of a fire (Alkhatib, 2014)

Examples of aerial surveillance systems used for forest fire detection that incorporate satellites:

- MODIS (moderate resolution imaging spectroradiometer): MODIS is a key instrument aboard two NASA Earth Observing System (EOS) satellites that can detect active fires and hot spots around the world. The sensors on MODIS satellites detect the amount of heat being radiated from the Earth's surface, which can be used to identify the location of active fires. MODIS has 1 KM and 500 M of spatial resolution and it can detect fires as small as 10 m across and provides near-real-time data to firefighters and other first responders (Alkhatib, 2014)
- Landsat: The Landsat program is a series of Earth-observing satellites that provide multispectral data for monitoring and managing natural resources. The sensors on Landsat satellites can detect changes in vegetation, which can be an indicator of potential fire risk. The data from Landsat can be used to create fire risk maps and identify areas that may be at high risk of wildfire (Thapa *et al*., 2021)
- Sentinel-2: Sentinel-2 is a European Union earth observation mission that provides high-resolution multispectral imagery of the Earth's surface. The sensors on sentinel-2 satellites can detect changes in vegetation and identify areas that may be at high risk of wildfire. The data from sentinel-2 can be used to monitor forested areas and identify potential fires, providing early warning to firefighters and other first responders (Thapa *et al*., 2021)
- Fire towers: Fire towers are tall structures that are typically located on hilltops or other high points and used for fire detection and monitoring. Fire spotters can use binoculars or other optical instruments to scan the forest for signs of smoke or fire. Fire towers can be connected to a central monitoring system to facilitate communication with firefighters and other emergency responders (Alkhatib, 2014)

Aerial surveillance provides an important

complement to ground-based systems for forest fire detection. By using a combination of ground-based and aerial surveillance systems, forest managers can develop a comprehensive strategy for detecting and responding to wildfires. Aerial surveillance can also be used for forest fire prediction, in addition to detection. Here are some examples of how aerial surveillance is used for forest fire prediction (Thapa *et al*., 2021; Partheepan *et al*., 2023):

- Mapping vegetation and fuel types: Aerial imagery can be used to map the types of vegetation and fuel present in forested areas. This information can be used to predict the likelihood of a fire occurring and how quickly it may spread. For example, areas with high fuel loads and dense vegetation are more likely to experience fast-spreading fires
- Monitoring weather conditions: Aerial surveillance can also be used to monitor weather conditions, such as temperature, humidity, wind speed and direction. This information can be used to predict how weather conditions will affect the likelihood and behavior of fires. For example, high winds can cause fires to spread quickly, while high humidity can reduce the risk of fires
- Early warning systems: Aerial surveillance can be used to detect early signs of fire, such as smoke plumes or hot spots. This information can be used to trigger early warning systems, which can alert firefighters and emergency responders to the potential threat
- Real-time monitoring: Aerial surveillance can be used to provide real-time monitoring of fires as they occur. This information can be used to predict the behavior of the fire and determine the best course of action for controlling and suppressing it

Aerial surveillance plays an important role in forest fire prediction, in addition to detection. By using a combination of ground-based systems, aerial surveillance and remote sensing, forest managers can develop a comprehensive strategy for preventing and responding to wildfires.

Machine Learning-Based Approaches Used for Forest Fire Detection

Machine learning-based approaches are increasingly being used for forest fire detection due to their ability to automate the process of analyzing large amounts of data from various sources. Here are some examples of how machine learning is used for forest fire detection (Masoud *et al*., 2019; Grari *et al*., 2022):

- Image classification: Machine-learning algorithms can be trained to classify images from ground-based systems, aerial surveillance and remote sensing data into fire and non-fire categories. These algorithms use deep neural networks to learn patterns and features of fire and can identify even small smoke plumes that may not be visible to the naked eye
- Anomaly detection: Machine-learning algorithms can be used to detect anomalies in the data that may indicate the presence of a forest fire. These algorithms can detect sudden changes in temperature, humidity, wind direction, or other environmental factors that may be indicative of a fire fusion of multi-modal data: Machine learning algorithms can be used to fuse data from different sources such as satellite imagery, drone footage and ground-based cameras to provide a more comprehensive and accurate detection of forest fires
- Early warning systems: Machine-learning algorithms can be used to develop early warning systems that can detect fires in their early stages and alert fire departments and other emergency responders. These systems can use historical data, weather data and other environmental data to predict the likelihood of a forest fire occurring in a given area
- Fire spread prediction: Machine-learning algorithms can be used to predict the spread of a forest fire based on data such as topography, vegetation type, wind direction and humidity levels. This information can be used to inform decisions on how to best manage the fire

Overall, machine learning-based approaches are an effective way to detect forest fires and provide timely alerts to emergency responders, enabling them to take action quickly and potentially prevent the spread of the fire. By combining machine learning with other detection methods, forest managers can develop a comprehensive strategy for detecting and responding to forest fires. Machine learning-based approaches are also increasingly being used for forest fire prediction, which involves estimating the likelihood and severity of a potential fire before it occurs. Here are some examples of how machine learning is used for forest fire prediction (Bot and Borges, 2022):

- Fire risk assessment: Machine-learning algorithms can be used to predict the likelihood of a forest fire based on factors such as weather patterns, fuel moisture content and historical fire data. These algorithms can learn from past fires and weather conditions to identify areas at high risk of fire and provide recommendations for preventative measures such as controlled burns or vegetation management
- Fuel moisture content prediction: Machine-learning algorithms can be used to predict the fuel moisture content, which is a key factor that affects the severity and spread of a forest fire. These algorithms can use weather data, vegetation type and other environmental factors to predict the moisture content of the vegetation and provide early warning of potential fires

- Fire spread prediction: Machine-learning algorithms can be used to predict the spread of a forest fire based on data such as topography, vegetation type, wind direction and humidity levels. These algorithms can simulate the behavior of the fire under different conditions and provide accurate predictions of its spread and intensity
- Real-time monitoring: Machine-learning algorithms can be used to analyze real-time data from sensors and cameras to detect and predict the behavior of forest fires. These algorithms can learn from the data and adjust their predictions in real time to provide more accurate information to emergency responders
- Smoke prediction: Machine learning algorithms can be used to predict the trajectory and dispersion of smoke from forest fires, which can help emergency responders plan their response and protect vulnerable populations

Social Media-Based Approaches for Forest Fire Detection

Social media-based approaches for forest fire detection have become increasingly popular in recent years, especially as more people share information and images about fires on social media platforms. Here are some examples of how social media can be used for forest fire detection (Wu *et al*., 2020; Sakaki *et al*., 2010; Mukkamala, 2018; Jaber *et al*., 2018):

- Social media monitoring: Emergency responders can monitor social media platforms such as Twitter, Facebook and Instagram for posts related to forest fires. This can include posts from individuals reporting the fire or updates from local news outlets. Machine learning algorithms can be used to analyze the posts and identify those that are most relevant to the fire
- Image and video analysis: Social media platforms allow users to share images and videos in real-time, which can provide valuable information about the location, severity and spread of a forest fire. Machine learning algorithms can be used to analyze the images and videos for signs of smoke or flames and provide alerts to emergency responders
- Social listening: Social media platforms allow users to share information about the fire, such as the location, size and direction of the fire. Emergency responders can use social listening tools to track these conversations and identify trends and patterns that may be indicative of a forest fire
- Crowdsourced data collection: Social media platforms can be used to crowdsource data about the fire, such as the location of the fire and its size. Emergency responders can use this information to improve their understanding of the fire and develop better strategies for responding to it
- Public awareness: Social media can be used to raise public awareness about the dangers of forest fires and encourage individuals to take steps to prevent them. This can include sharing educational content about fire safety and providing updates on the current fire situation in a particular area

Social media-based approaches can be a valuable tool for detecting forest fires and providing timely alerts to emergency responders. Social media-based approaches for forest fire prediction are still in their infancy and are not yet widely used. However, there are some potential applications of social media for predicting forest fires (Wu *et al*., 2020; Sakaki *et al*., 2010; Mukkamala, 2018)

- Early warning systems: Social media can be used to identify trends and patterns that may be indicative of a forest fire. For example, an increase in posts about smoke or flames in a particular area could signal the start of a fire. Machine learning algorithms can be used to analyze this data and provide early warning alerts to emergency responders
- Crowdsourced data collection: Social media can be used to crowdsource data about environmental conditions that may be relevant to forest fire prediction. For example, users can share information about the presence of dry or dead vegetation in a particular area, which can increase the risk of a fire
- Public awareness: Social media can be used to raise public awareness about the importance of preventing forest fires and encourage individuals to take steps to 13 reduce their risk. This can include sharing educational content about fire prevention and providing updates on the current fire situation in a particular area

Overall, social media-based approaches have the potential to provide valuable information for predicting forest fires. However, more research is needed to develop effective algorithms for analyzing social media data and integrating it with other prediction methods. Additionally, privacy concerns and data reliability issues must be addressed before social media-based approaches can be widely adopted.

Conclusion

As we reach the end of this survey paper on forest fire detection, prediction and behavior analysis techniques, we can see that the topic of forest fires is complex and multifaceted, with numerous challenges to address. Forest fires can have devastating effects on natural resources,

wildlife and human communities. However, by using a combination of ground-based systems and aerial surveillance technologies, as well as machine learning-based approaches, it is possible to detect and predict forest fires and to understand their behavior in real time.

Ground-based systems such as infrared cameras, flame detectors, thermal sensors, weather stations, smoke detectors and acoustic sensors can be used to detect fires and provide real-time data to firefighters and other first responders. Aerial surveillance systems such as drones and satellites can provide a broad view of forested areas and can detect fires that may be difficult to see from the ground. These systems provide early warning to firefighters and other first responders, allowing them to respond quickly and effectively to forest fires.

Machine learning-based approaches such as image classification techniques can be used to identify fires in near-real-time, helping to detect fires earlier and provide early warning to first responders. These approaches can also be used to understand the behavior of forest fires and predict their spread, allowing for more effective and targeted firefighting efforts.

There is also a need for continued research into the underlying causes of forest fires, including climate change and human activities, as well as the development of effective strategies for preventing and managing forest fires. This will require collaboration between scientists, policy makers and stakeholders at all levels, as well as continued engagement with local communities and indigenous peoples who have valuable knowledge and expertise in managing and preventing forest fires.

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Author's Contributions

Ahmad Alkhatib: Conducted background research, designed and executed experiments, analyzed data and authored the manuscript.

Khalid Jaber: Assisted in drafting the manuscript, provided critical insights and contributed to paper formatting, figures and diagrams.

Ethics

The corresponding author confirms that all of the other authors have read and approved the manuscript and that no ethical issues are involved.

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