



# Drones in Plant Disease Management

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Forest diseases pose a significant threat to global forest ecosystems, exposing biodiversity, carbon storage capacity, and valuable timber resources. Pathogens such as *Phytophthora ramorum* (sudden oak death), *Austropuccinia psidii* (myrtle rust), *Hymenoscyphus fraxineus* (ash dieback), and *Cryphonectria parasitica* (chestnut blight) are spreading rapidly, exacerbated by climate change and human activities. Conventional monitoring methods, such as ground surveys, are typically labor-intensive, time-consuming, and insufficient for early-stage detection of these diseases. In contrast, Unmanned Aerial Vehicles (UAVs) equipped with advanced remote sensing technologies offer a high-resolution, scalable, and cost-effective approach to forest health evaluations. This chapter synthesizes current research on UAV-based forest disease monitoring, with a particular focus on the integration of multispectral, hyperspectral, thermal, and LiDAR sensors for early pathogen detection and management. UAVs have demonstrated their ability to successfully identify a range of forest diseases through machine learning-driven spectral analysis, 3D canopy mapping, and thermal anomaly detection. UAVs provide distinct advantages over traditional methods, including rapid data acquisition, real-time monitoring, and access to remote and difficult-to-reach terrains. Fusing UAV data with satellite imagery and artificial intelligence (AI) algorithms further enhances predictive modelling, enabling more proactive and efficient disease management. Despite these advancements, challenges such as limited flight endurance, sensor calibration inconsistencies, and regulatory restrictions hinder their widespread use.

**Keywords:** UAVs, Forest disease monitoring, Remote sensing, Machine learning, Early detection

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Future research should prioritize standardizing monitoring protocols, improving sensor sensitivity for pre-symptomatic disease detection, and developing autonomous UAV systems for large-scale forest monitoring. Integrating UAV technology into forest management frameworks holds the potential to revolutionize disease surveillance, supporting global

conservation efforts to preserve forest ecosystems in the face of increasing climate and anthropogenic pressures.

## Introduction

Forests are among the most critical ecosystems on Earth, playing an indispensable role in maintaining environmental stability and supporting human well-being. They deliver a wide array of ecosystem services, including carbon sequestration, climate regulation, water filtration, soil stabilization, and the conservation of biodiversity (Eger et al., 2023). As global environmental pressures mount, the importance of these services becomes even more pronounced. However, forests are increasingly threatened by the multifaceted impacts of climate change. Rising global temperatures, altered precipitation patterns, and the increasing frequency and severity of extreme weather events have intensified both biotic and abiotic stressors on forest ecosystems (Seidl et al., 2014; Pörtner et al., 2022). These stressors compromise forest health and resilience, diminishing the ability of forests to continue providing vital services. Among the most pressing challenges to forest sustainability are diseases caused by pathogens such as fungi, bacteria, viruses, and phytoplasmas. Monitoring and managing these threats is essential not only for conserving biodiversity and forest structure but also for supporting the ecological services that forests provide to society. Timely and effective monitoring of forest diseases enables the early identification of emerging threats, thereby facilitating targeted interventions to minimize damage. Understanding the dynamics and progression of tree diseases is therefore a cornerstone of ecological resilience, helping to safeguard forests against long-term degradation (Park and Choi, 2019).

In recent years, remote sensing technologies have been widely adopted for forest health assessment. While satellite and aerial imagery provide valuable data at broad scales, they often lack the spatial and temporal resolution needed to detect early or localized signs of tree stress (Lausch et al., 2016; Lechner et al., 2020). Physiological responses in trees, such as changes in leaf pigment or moisture content, may precede visible symptoms like wilting or defoliation and often go undetected by coarse-resolution sensors (Schuldt et al., 2020). Consequently, more precise monitoring methods are required to capture these subtle yet critical indicators of disease onset. Addressing forest disease effectively requires a comprehensive approach that combines traditional ecological knowledge with advanced monitoring technologies. This chapter introduces the significance of forest disease surveillance in the context of climate change and outlines the potential of emerging technologies, such as high-resolution remote sensing and unmanned aerial vehicles (UAVs), in enhancing our ability to monitor, understand, and manage forest health.

**Table 1. Studies on UAV-based forest disease monitoring**

Source	Study area	UAV type	Sensor	Host	Disease & causative organism
Park & Kim (2014)	South Korea	Fixed-Wing	RGB	Pine ( <i>Pinus</i> sp.)	Pine wilt disease ( <i>Bursaphelenchus xylophilus</i> )
Smigaj et al., (2015)	United Kingdom	Fixed-Wing	Thermal, multispectral	Pine ( <i>Pinus sylvestris</i> , <i>P.contorta</i> )	Red band needle blight ( <i>Dothistroma septosporum</i> )
Michez et al., (2016)	Belgium	Fixed-Wing	RGB, multispectral	Black alder ( <i>Alnus glutinosa</i> )	Black alder disease ( <i>Phytophthora alni</i> )
Brovkina et al., 2018	Czech Republic	Multirotor	RGB, multispectral	Norway spruce ( <i>Picea abies</i> )	Honey fungus ( <i>Armillaria ostoyae</i> )

Ganthaler et al., (2018)	Austria	Multicopter	RGB	Norway spruce ( <i>Picea abies</i> )	Needle bladder rust disease ( <i>Chrysomyxa rhododendri</i> )
Sandino et al., (2018)	Australia	Multicopter	Hyperspectral	Paperbark tea tree ( <i>Melaleuca quinquenervia</i> )	Myrtle rust ( <i>Austropuccinia psidii</i> )
Dell et al., (2019)	Indonesia	Multicopter	RGB	Eucalyptus ( <i>Eucalyptus pellita</i> )	Bacterial wilt ( <i>Ralstonia</i> sp.)
Jung & Park (2019)	South Korea	Fixed-Wing	RGB, multispectral	Pine ( <i>Pinus</i> sp.)	Pine wilt disease ( <i>Bursaphelenchus xylophilus</i> )
Lee et al., (2019)	South Korea	Multicopter	RGB	Oak ( <i>Quercus mongolica</i> , <i>Q. serrata</i> , <i>Q. dentata</i> )	Oak wilt ( <i>Raffaelea quercus-mongolicae</i> )
Smigaj et al., (2019)	United Kingdom	Multicopter	Thermal	Scots pine ( <i>Pinus sylvestris</i> )	Red band needle blight ( <i>Dothistroma septosporum</i> )
Kampen et al., (2019)	Austria	Multicopter	Multispectral	Norway spruce ( <i>Picea abies</i> ), European ash ( <i>Fraxinus excelsior</i> )	Ash dieback ( <i>Hymenoscyphus pseudoalbidus</i> )
Pádua et al., (2020)	Portugal	Multicopter	RGB, multispectral	Sweet chestnut ( <i>Castanea sativa</i> )	Ink disease ( <i>Phytophthora cinnamomi</i> ), blight ( <i>Cryphonectria parasitica</i> )
Hoshikawa & Yamamoto (2020)	Japan	Multicopter	RGB, multispectral	Japanese black pine ( <i>Pinus thunbergii</i> )	Pine wilt disease ( <i>Bursaphelenchus xylophilus</i> )
Honkavaara et al., (2020)	Finland	Multicopter	RGB, multispectral, thermal, hyperspectral	Norway spruce ( <i>Picea abies</i> )	Root and butt rot ( <i>Heterobasidion annosum</i> )
Qin et al., (2021)	China	Multicopter	Multispectral	Chinese red pine ( <i>Pinus massoniana</i> )	Pine wilt disease ( <i>Bursaphelenchus xylophilus</i> )
Yu et al., (2021a)	China	Multicopter	RGB, Hyperspectral, LiDAR	Korean pine ( <i>Pinus koraiensis</i> )	Pine wilt disease ( <i>Bursaphelenchus xylophilus</i> )
Yu et al., (2021b)	China	Multicopter	Hyperspectral	Chinese pine ( <i>Pinus tabulaeformis</i> )	Pine wilt disease ( <i>Bursaphelenchus xylophilus</i> )

### Forest tree diseases

Forest ecosystems worldwide are increasingly threatened by a variety of diseases caused by fungal, bacterial, viral, and phytoplasma-like pathogens. These diseases can significantly impair tree health, reduce biodiversity, and disrupt ecosystem functionality, ultimately undermining the capacity of forests to provide

critical ecological services. Among these pathogens, fungal diseases represent one of the most severe and widespread threats to forest stability. One of the most notable fungal pathogens is *Armillaria* spp., the causative agent of Armillaria root rot. This disease affects a wide range of tree species across both boreal and tropical forests, leading to root decay, reduced growth, and often tree mortality (Sazonov et al., 2023). Similarly, *Cryphonectria parasitica*, responsible for chestnut blight, has devastated chestnut populations, particularly in North America and parts of Europe (Romon-Ochoa et al., 2022). Another significant fungal threat is *Hymenoscyphus fraxineus*, the causal agent of ash dieback, which poses a critical risk to ash populations across Europe and beyond (Marçais et al., 2022). *Phytophthora ramorum*, a notorious oomycete pathogen, causes sudden oak death and has been widely reported in both the United States and Europe. It results in widespread canopy dieback and mortality in susceptible oak species (Kang et al., 2024). In the Southern Hemisphere, particularly Australia, *Austropuccinia psidii*, the pathogen behind myrtle rust, has caused extensive damage to numerous species within the *Myrtaceae* family (Sandino et al., 2018). Similarly, *Corticium salmonicolor*, the fungal agent of pink disease, affects a broad range of woody plant species, especially in tropical regions (Indrioko et al., 2021). Bacterial pathogens also contribute significantly to forest decline. Fire blight, caused by *Erwinia amylovora*, is a well-documented disease in both agricultural and natural woody plant systems. In addition, *Ralstonia solanacearum* and *Xylella fastidiosa*, both associated with wilt and leaf scorch symptoms, cause rapid decline in several forest species, especially under concurrent stress from drought or insect infestation (Dennert et al., 2024). Viral and phytoplasma-associated diseases, though often less conspicuous, can also have substantial ecological impacts. *Taphrina caerulescens*, the agent of oak leaf curl, can alter leaf physiology and reduce photosynthetic capacity, while phytoplasma-linked diseases such as sandal spike in *Santalum album* severely affect tree growth and survival, particularly in tropical and subtropical zones (Bandte et al., 2020; Mondal et al., 2020). Alarmingly, many of these diseases are expanding their geographic range, driven in large part by climate change. Warmer temperatures, increased humidity, and altered precipitation patterns create favorable conditions for pathogen survival, reproduction, and dispersal. Additionally, increased global trade and the movement of plant materials further accelerate the spread of invasive forest pathogens across biogeographic boundaries.

### **Emergence of UAVs in forest tree disease monitoring**

Unmanned Aerial Vehicles (UAVs), commonly referred to as drones, have emerged as transformative tools in the field of forest disease monitoring. By bridging the gap between detailed, labor-intensive ground surveys and broad-scale satellite observations, UAVs offer a cost-effective and efficient method for collecting high-resolution spatial and temporal data. Their ability to operate in remote or difficult terrain enables comprehensive coverage, making them particularly valuable for detecting early signs of tree stress and disease across diverse forest ecosystems. Drones can capture critical information on tree health safely, repeatedly, and with minimal disruption to the environment. Their adaptability has led to a growing number of studies utilizing UAVs to monitor tree responses to both biotic and abiotic stressors. For instance, Dash et al., (2017) successfully applied UAVs to detect *Phytophthora agathidicida*, the pathogen behind kauri dieback in New Zealand, and *Austropuccinia psidii*, the causative agent of myrtle rust in various plant species. Similarly, Ganthaler et al., (2018) employed UAV-based methods to assess conifer diseases such as root and butt rot caused by *Heterobasidion annosum* in European forests. Advances in sensor technology have further enhanced the utility of UAVs in disease detection. Hyperspectral imaging, in particular, has proven effective for early identification of subtle physiological changes associated with infection. Dainelli et al., (2021) utilized UAV-mounted hyperspectral sensors to detect *Xylella fastidiosa* in olive trees in Apulia, Italy. In another case, Guliutin and Antamoshkin (2024) developed a modified YOLO (You Only Look Once) deep learning model for UAV-based imagery, improving early detection of pine needle blight caused by

*Dothistroma septosporum* in Siberian pine forests by 37% over traditional techniques. The integration of spatial context and advanced image analysis has also expanded the analytical capabilities of UAVs. Hornero et al., (2022) demonstrated that combining multispectral imagery with object-based image analysis (OBIA) effectively detected sudden oak death (*Phytophthora ramorum*) through canopy discoloration in California forests. Furthermore, hyperspectral and thermal sensors have enabled the assessment of water stress and canopy temperature anomalies associated with diseases such as chestnut blight (*Cryphonectria parasitica*) in Italy and olive quick decline syndrome in Spain (*Xylella fastidiosa*) (Zarco-Tejada et al., 2018; Dainelli et al., 2021). Artificial intelligence and machine learning algorithms have further propelled UAV applications in forest health surveillance. Convolutional neural networks (CNNs), for instance, have been successfully employed to detect *Puccinia psidii* (Eucalyptus rust) in Brazil with 94% classification accuracy (Bouffleur et al., 2023). Likewise, CNNs have been applied in China to map pine wilt disease caused by the nematode *Bursaphelenchus xylophilus* (Ding et al., 2022). In addition to spectral and thermal imaging, structural mapping using LiDAR (Light Detection and Ranging) has shown great promise. A study in Germany combined LiDAR-derived canopy height models with NDVI (Normalized Difference Vegetation Index) to track the progression of beech bark disease caused by *Neonectria* spp. (López-García et al., 2024). Integration of UAV and satellite data has also proven effective for scaling up monitoring efforts, as demonstrated by Thornley (2018) in Denmark, where UAV imagery complemented satellite observations to monitor ash dieback caused by *Hymenoscyphus fraxineus*. Emerging feature extraction techniques, such as the Photochemical Reflectance Index (PRI), have further improved the detection of pre-symptomatic infections. Hlaiem et al. (2023) used this approach to successfully detect early signs of *Diplodia pinea* infection in Portuguese pine forests, highlighting the importance of early intervention strategies enabled by UAV surveillance. Collectively, these advancements underscore the transformative role of UAVs in forest pathology. By enabling precise, high-resolution monitoring of forest health and facilitating early detection of disease, UAVs are becoming indispensable tools in the fight to preserve forest ecosystems in the face of emerging biotic threats and climate change.

### Sensor-based drone technologies available for forest disease monitoring

The effectiveness of unmanned aerial vehicles (UAVs) in forest disease monitoring is largely determined by the types of remote sensing sensors they carry. These sensors are broadly classified into two categories: passive sensors, which depend on ambient light, and active sensors, which emit their signals to gather data. Each sensor type offers distinct advantages and plays a crucial role in the early detection and analysis of forest invasive pathogens.

**Passive sensors:** Passive sensors are widely used in UAV-based forest monitoring due to their accessibility, affordability, and compatibility with commercially available drones.

- **RGB cameras:** Red-Green-Blue (RGB) cameras capture visible light within the 400–700 nm spectrum. They are commonly mounted on consumer-grade drones such as the DJI Phantom series and are effective for capturing general imagery and conducting preliminary disease assessments (Manfreda et al., 2018; Cardil et al., 2017). Despite their simplicity, RGB images can reveal symptoms such as discoloration, defoliation, and canopy thinning.
- **Multispectral sensors:** These sensors extend detection capabilities beyond the visible spectrum into the near-infrared (NIR >700 nm) range, enabling more precise identification of plant stress responses. Instruments such as the Parrot Sequoia and Micasense RedEdge MX have become standard tools for

UAV-based forest health monitoring. When paired with RGB sensors, multispectral data significantly enhances the ability to detect disease-induced physiological changes in vegetation (Cardil et al., 2019; Iordache et al., 2021).

- **Hyperspectral sensors:** For more granular analysis, hyperspectral sensors such as the Nano-Hyper spec and Pika L. provide ultra-high spectral resolution by capturing data across hundreds of narrow bands. These sensors are capable of detecting subtle biochemical and physiological changes that may occur before visible symptoms manifest. However, their high cost, large data volumes, and need for high-payload UAV platforms like the DJI Matrice 600 present practical challenges in routine deployment (Zhang et al., 2019; Lin et al., 2017).
- **Thermal sensors:** Thermal imaging sensors measure canopy temperature variations, which can serve as early indicators of stress caused by pathogen infection, drought, or insect infestation. Thermal data is particularly useful for identifying localized heat anomalies associated with diseases such as red band needle blight or mistletoe infestations (Smigaj et al., 2019).

**Active sensors:** Active sensors emit their signals, typically in the form of laser pulses or radar waves, and are particularly valuable for structural analysis of forest stands.

- **LiDAR (Light Detection and Ranging):** LiDAR sensors, such as the LiAir 200, generate high-resolution 3D data that can be used to assess tree height, crown structure, and canopy density. When integrated with spectral data, particularly from hyperspectral sensors, LiDAR enables comprehensive forest health assessments by correlating structural degradation with physiological stress (Yu et al., 2021).

**Sensor integration and synergy:** Integrating different sensor types, such as combining RGB with multispectral or LiDAR with hyperspectral imaging, enhances diagnostic accuracy and enriches the dataset available for disease detection. This multi-sensor approach enables UAV systems to capture not only visual symptoms but also physiological and structural indicators of disease progression. While RGB and multispectral sensors remain the most widely adopted due to their cost-effectiveness and operational simplicity, hyperspectral imaging offers superior sensitivity for early-stage detection, albeit at a higher financial and computational cost (Tmušić et al., 2020; Zhang et al., 2020). The choice of sensor technology should therefore be aligned with monitoring objectives, disease characteristics, and resource availability.

### **Benefits of UAVs over traditional methods**

The adoption of unmanned aerial vehicles (UAVs), or drones, in forest disease monitoring has transformed traditional surveillance and assessment approaches. Compared to conventional methods such as ground-based surveys or satellite remote sensing, UAVs offer a range of operational, spatial, and analytical advantages that enable more effective and timely detection of forest health issues.

**Enhanced spatial coverage and image resolution:** One of the primary advantages of UAVs lies in their ability to cover large forested areas rapidly while capturing high-resolution imagery. Traditional ground-based surveys are labor-intensive and time-consuming, often limited by difficult terrain or inaccessibility. UAVs, on the other hand, enable rapid data acquisition across broad landscapes, allowing forest managers to

assess tree health at fine spatial scales. Ecke et al. (2022) emphasized the value of UAV-based remote sensing for improving monitoring efficiency, particularly in comparison with conventional survey techniques.

**Early detection through advanced sensor technologies:** Equipped with advanced imaging systems, such as multispectral and hyperspectral sensors, UAVs can detect subtle physiological and biochemical changes in vegetation before visible symptoms emerge. Tsiamis et al., (2019) highlighted the ability of UAV-mounted sensors to identify early indicators of disease, supporting pre-symptomatic diagnosis. Similarly, Mahmudnia et al., (2022) demonstrated how drones enhance early stress detection, enabling forest managers to initiate timely and proactive interventions.

**Temporal flexibility and disease progression monitoring:** UAVs provide high temporal resolution, enabling repeated data collection over short intervals. This allows for continuous monitoring of disease progression and recovery across seasonal and phenological stages. Harris et al., (2022) noted the capacity of drones to track the temporal dynamics of forest disease, offering crucial insights into the spatial spread and impact of pathogenic outbreaks.

**Real-time data availability and rapid response capabilities:** Another major benefit is the capacity for near-real-time data collection and analysis. This is particularly important in managing sudden disease outbreaks where rapid decision-making is essential. Oliveira et al., (2018) underscored that real-time UAV data processing facilitates swift responses to emerging threats, such as pathogen spread or environmental stressors, improving forest management efficacy.

**Integration with artificial intelligence for advanced analysis:** The convergence of UAV technology with artificial intelligence (AI) has opened new avenues for forest disease diagnostics. Advanced algorithms, including machine learning and deep learning, are increasingly used to analyze UAV-acquired datasets, enabling automated disease classification and prediction. Udali et al., (2023) emphasized the role of AI in extracting valuable insights from large UAV datasets, thereby enhancing the accuracy and speed of forest health assessments. For example, UAV-based hyperspectral imaging has proven effective in identifying specific pathogens across various plant species. Dainelli et al., (2021) successfully detected *Flavescence dorée*, a destructive grapevine yellow disease caused by phytoplasmas, in Italian vineyards (*Vitis vinifera*). Similarly, Abdulridha et al., (2020) utilized UAV imagery to identify bacterial pathogens such as *Xanthomonas axonopodis* pv. *Citri* (citrus canker) and *Candidatus Liberibacter asiaticus* (citrus greening) affecting citrus orchards in Florida, USA.

### **The drawbacks of UAV-based forest disease monitoring approaches**

Despite the growing success of UAV-based technologies in forest disease surveillance, several practical, technical, and regulatory constraints continue to hinder their broader adoption and scalability. Understanding these limitations is essential for guiding future research and refining operational frameworks for UAV integration in forest health management.

**Limited operational range and payload capacity:** A primary limitation of UAV systems is their restricted battery life and limited payload capacity, which constrain their operational range and endurance. These constraints limit the feasibility of monitoring large, continuous forested landscapes, particularly in the case of widespread infections such as *Phytophthora ramorum*, the causal agent of sudden oak death. Frequent recharging and multiple flight missions are often required, increasing logistical complexity and costs.

**Sensor and spectral limitations:** Although multispectral and RGB cameras are widely used for UAV-based disease detection due to their accessibility and cost-effectiveness, they may lack the spectral resolution necessary to detect early or subtle signs of infection. Critical biochemical and physiological indicators may go unnoticed without the use of more advanced hyperspectral or thermal sensors, which are costlier and require higher payload capacity drones. This technological gap limits early intervention strategies, especially for diseases such as *Austropuccinia psidii* (myrtle rust), where early symptom detection is crucial (Bouffleur et al., 2023).

**Calibration and data consistency issues:** Multi-temporal monitoring, essential for tracking disease progression, faces challenges related to sensor calibration, illumination variability, and atmospheric interference across different flight sessions. These inconsistencies can introduce errors in data interpretation, complicating efforts to detect changes over time, particularly in slow-developing or phenology-sensitive diseases.

**Methodological and analytical constraints:** Object-based image analysis (OBIA), commonly used in UAV data processing, can sometimes fail to capture contextual spatial information critical for accurate disease detection. Diseases with irregular spatial distribution or overlapping symptoms may not be effectively identified. Additionally, while deep learning models have shown high accuracy in classification tasks, their application often involves significant computational resources and expertise, posing a barrier to widespread implementation in operational forestry settings (Thornley, 2018).

**Regulatory and logistical barriers:** Legal and regulatory restrictions on UAV flights, particularly in protected areas or during certain seasons, can impede timely data collection. Such limitations are especially problematic for tracking phenology-dependent diseases like pine tip blight (*Diplodia pinea*), where data acquisition must align with specific developmental stages (Hlaiem et al., 2023). Moreover, complex airspace regulations and requirements for pilot certifications can restrict UAV deployment in many jurisdictions.

**Need for integrated solutions:** These limitations underscore the necessity for ongoing technological advancements and the integration of complementary tools, such as satellite data, ground-based observations, and improved analytical models, to enhance the accuracy and utility of UAV-based monitoring. Innovations in battery life, autonomous flight planning, sensor miniaturization, and AI-driven processing will be critical to overcoming current challenges and optimizing UAV applications in forest disease surveillance.

### **Future research directions in UAV-based forest disease monitoring**

As UAV technology continues to evolve, future research in forest disease monitoring should focus on the integration of advanced tools and methodologies to enhance early detection, improve spatial-temporal analysis, and support proactive forest management strategies. This is particularly crucial in tropical and remote forested regions, where dense canopies and difficult terrain hinder traditional ground-based surveillance efforts. UAVs present a highly adaptable and efficient solution for monitoring in such environments, and their application should be further optimized and expanded. A key priority for future studies is the standardization of UAV flight parameters and sensor configurations across diverse ecological zones. Establishing standardized protocols will ensure data consistency, improve comparability among studies, and support the development of global forest health monitoring frameworks. Additionally, the integration of UAV-acquired data with high-resolution satellite imagery can expand spatial coverage and enable hierarchical disease surveillance systems that address both localized symptoms and landscape-scale

outbreaks. Emerging artificial intelligence techniques, such as deep learning, genetic algorithms, and evolutionary computing, hold significant promise for advancing disease classification accuracy and automating the analysis of large UAV datasets. These tools can be particularly effective when trained on multispectral, hyperspectral, and thermal imagery, allowing for the detection of pre-symptomatic stress signals that are not visible to the human eye. Further innovation is needed in the development and deployment of next-generation sensor technologies. Hyperspectral imaging, in particular, provides high spectral resolution that is essential for identifying subtle biochemical changes associated with early-stage infections. Pairing such sensors with advanced feature selection and extraction methods will enhance the interpretability of complex datasets. Longitudinal studies and long-term UAV-based monitoring programs are also essential to deepen our understanding of forest disease dynamics over time. These efforts can inform the development of predictive models that incorporate climate, topographic, and biological variables, thus supporting timely and targeted management interventions.

## **Conclusion**

Unmanned Aerial Vehicles (UAVs) have transformed forest disease monitoring by enabling high-resolution, efficient, and scalable data collection across diverse and often inaccessible ecosystems compared to the traditional methods. Their integration into forest health surveillance has significantly advanced the early detection, mapping, and management of pathogenic threats, contributing to the resilience and sustainability of global forest ecosystems. By combining UAVs with advanced remote sensing technologies, including hyperspectral imaging, thermal sensors, multispectral systems, and LiDAR, researchers and forest managers can now detect disease symptoms at pre-visual stages. These technologies, when paired with artificial intelligence and machine learning algorithms, enhance diagnostic precision, automate classification, and allow predictive modelling to anticipate disease spread. Such capabilities are vital for enabling early interventions that mitigate both economic losses and ecological degradation in the era of accelerating climate change. Its application not only improves the management of forest health but also contributes to broader goals such as biodiversity conservation, carbon sequestration, and ecosystem service preservation. The adoption of UAV's technology for forest disease surveillance and management is especially crucial in tropical countries, where it remains underutilized despite its proven effectiveness in other regions of the world.

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