PLANT SCIENCE TODAY
Vol x(x): xx–xx
https://doi.org/10.14719/pst.8169

eISSN 2348-1900

REVIEW ARTICLE

Advancements in UAV technology for forestry applications: A comprehensive review

R Madesh[1], R Ravi[1*], K Baranidharan[1], M Vijayabhama[2], K P Ragunath[3], P Hemalatha[1], A Harish[1] & S Satheesh[2]

[1]Forest College and Research Institute, Tamil Nadu Agricultural University, Mettupalayam 641 305, Tamil Nadu, India
[2]Department of Statistics, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[3]Department of Geospatial and Water Studies, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

*Correspondence email - ravi.r@tnau.ac.in

Received: 10 March 2025; Accepted: 24 June 2025; Available online: Version 1.0: 08 September 2025

Cite this article: Madesh R, Ravi R, Baranidharan K, Vijayabhama M, Ragunath KP, Hemalatha P, Harish A, Satheesh S. Advancements in UAV technology for forestry applications: A comprehensive review. Plant Science Today (Early Access). https:/doi.org/10.14719/pst.8169

Abstract

The rapid growth of Unmanned Aerial Vehicles (UAVs) or Drones have significantly revolutionized the methodologies of modern forestry. Traditional methods being dependent on low resolution satellite data and labour-intensive field work are now being substituted by high resolution drone-based data offering real time monitoring and increased operational efficiency. This review examines the extensive role of UAVs in modernising various forestry practices and its associated challenges. Different types of drones namely, fixed-wing, rotary-wing and hybrid models along with advance imaging systems and sensors such as multispectral, hyperspectral, thermal and LiDAR sensors. These technologies have been proven as inevitable source of forest inventory, health monitoring, wildfire detection and suppression, biodiversity assessment and precision forestry. UAVs Provide high resolution 3D Modelling, early disease detection and pest monitoring and improved seed dispersal through precision techniques. Apart from that usage of machine learning and deep learning technologies have enabled the usage of drone swarms enhancing large scale autonomous operation like real time environment monitoring. Despite their extensive advantages UAVs also have some minor disadvantages including regulatory constrains like lack of data processing, sensor limitation and high investment cost. In the Indian context though drone regulations are evolving there are some lacks on policy enforcement and legal framework. The review insists upon the need for unified legal frameworks, improved data-sharing methodologies and open-source software to support the wider adoption of UAVs in forestry. As drone technology continues to advance with blockchain interpretation, energy harvesting and user-friendly systems, its role in sustainable forest management is set to expand. UAVs are emerging as indispensable tools for efficient, responsive and ecologically responsible forestry practices.

Keywords : canopy mapping; drones in forestry; forest monitoring; LiDAR and multispectral imaging; remote sensing; UAV regulations and challenges; wildlife monitoring

Introduction

The integration of Unmanned Aerial Vehicles (UAVs), commonly known as drones, represents one of the most significant technological advancements in modern forestry management and conservation. Traditional forestry practices have long relied on labour-intensive field surveys, limited aerial photography and satellite imagery with inherent resolution constraints (1). The emergence of drone technology has revolutionized these approaches, offering unprecedented capabilities for data collection, monitoring and management of forest ecosystems. Drones provide forestry professionals with a versatile platform capable of capturing high-resolution imagery and precise measurements across various spatial and temporal scales (2). From fixed-wing models designed for extensive area coverage to highly manoeuvrable rotary-wing units equipped with sophisticated sensors, these aerial systems have dramatically reduced the time, cost and logistical challenges associated with forest assessments (3). The technology bridges the critical gap between ground-based observations and satellite imagery, delivering detailed data that was previously unattainable. The applications of drone technology in forestry are remarkably diverse. Forest managers now employ UAVs to create detailed Ortho mosaic maps and digital elevation models, conduct accurate forest inventories, monitor canopy health, detect early signs of disease and pest infestations and support precision forestry operations (4, 5). Advanced sensor technologies-including multispectral, hyperspectral, LiDAR and thermal imaging-have further expanded these capabilities, enabling comprehensive analysis of forest structures, species composition and ecosystem health (6). Beyond operational efficiency, drones are proving instrumental in addressing pressing environmental challenges. They enhance biodiversity monitoring (7), assist in tracking invasive species (4), provide critical data for wildfire management (8) and support community-based conservation initiatives (9). In regions where illegal logging threatens forest ecosystems, drone surveillance offers a cost-effective solution for enforcement and protection (10).

Fundamentals of drone technology

Classification of UAVs

We consider fixed wing UAVs as a class of UAVs that have airplane type structure that gives high gliding efficiency while flying through air. Because they consume little energy for large distances, they are generally used for long range missions. However, they depend on runways for take-off and landing and thus, tend to be inflexible from operational point of view (11). A highly manoeuvrable and capable of VTOL type rotary wing UAVs are quadcopters. As such, they are very suitable for hovering and precise activities such as surveillance, inspection and search and rescue. Quadcopter is one of the most common classes under this category, it is easy to use and effective for many applications (12). It is a UAV hybrid with fixed wing and rotary wing design, which thus allows for long range flight and VTOL. Nevertheless, these UAVs have gained popularity and they offer a higher flexibility and perform more, generally, other than the usual UAVs without limiting them (11). Various classes of UAVs are depicted in Fig. 1.

Categories of UAVs based on propellers

Typically, these are fixed wing UAVs which make a single propeller thrust. They are efficient for travel long distances but need runways at take-off and landing (13). Dual-Propeller UAVs come in the form of Coaxial Configurations, or dual propeller setups which allow to increase load capacity without propeller diameter grow. Such a configuration is suitable for applications with higher lift needed (for example, rescue) (14). The quadrotor UAVs are quite often available with four propellers. They are stable and manoeuvrable and thus suitable for such applications as surveillance and delivery. Furthermore, their mobility is inherently underactuated (15). These UAVs are hexacopter and octocopter UAVs that have six and eight propellers, respectively. Quadrotors are very unstable and have limited arm payloads. Redundancy of the additional propellers is required for reliable applications, like in rescue missions (14). Some of the common drone features are summarized in Table 1 and various drone power sources are mentioned in Table 2.

Types of cameras in drone

Drones are fitted with hyperspectral cameras that capture the detail of spectral information recorded over certain wavelengths. These include a palm size 2D spectroscopic imager for mid-infrared lights and the thumb size 1D snapshot hyperspectral camera which enables high time resolution and simple optics without mechanical movements (16). Underwater drones are also used to capture images horizontally, using cameras that have panoramic capabilities, such as 360°. When fisheye lenses are used in these cameras, the images at a fixed sampling density provide a complete view that is necessary for tasks with wide coverage or detailed environmental monitoring (17). Moreover, drones are identified using drone detection systems, in which fisheye camera are used to monitor wide sky areas, increasing the number of rotational axis to be able to track and detect aerial objects (18). Low latency, event camera sensors that provide bioinspired, low latencies, required for dynamic obstacle avoidance with drones are provided. As such, these cameras do not capture traditional images but rather return a stream of asynchronous events corresponding to intensity changes, which allow drones

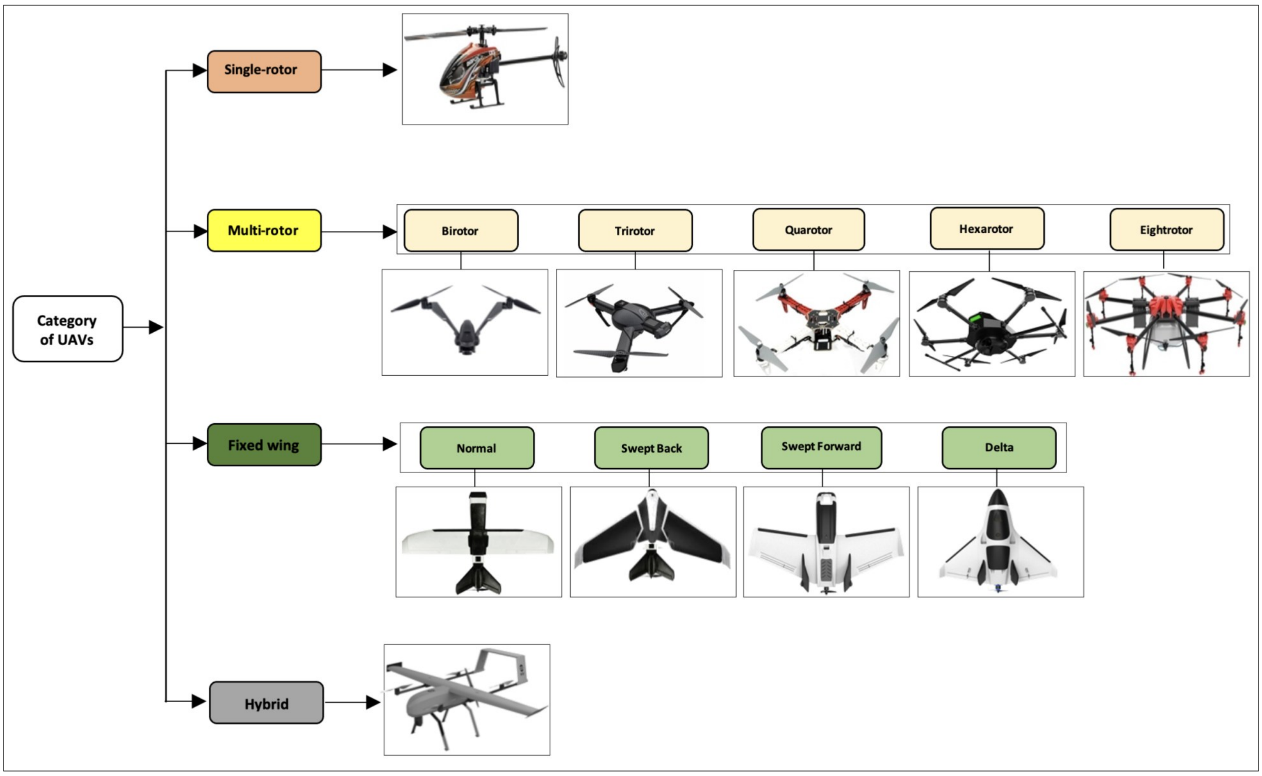

Fig. 1. Classification of UAVs based on their rotors. Source Ref. (61).

Table 1. Common drone features

Feature	Fixed-wing drones	Rotary-wing drones
Take-off/landing	Horizontal	Vertical
Coverage area	Higher	Lower
Stability	Lower	Higher
Spatial Resolution	Lower	Higher

Table 2. Drone power supply

Feature	Electric drones	Internal combustion drones
Suitability for remote sensing	Higher	Lower
Economy	Higher	Lower
Vibration	Lower	Higher

to quickly react to a fast-moving object (19). For drones, depth cameras, which are usually used with tracking cameras, are essential for 3D mapping and indoor navigation. With the help of these cameras, it is easier to capture point clouds and keep the drone's pose stable for the purpose of more accurate 3D reconstructions of environments (20). Drones that use thermal infrared cameras are used to monitor wildlife and to carry out population studies. As these cameras can distinguish one species from another based-on body measurements and recognize, the animal and follow it from a great height these cameras are useful for ecological research and the conservation work (21). Typically, in drone detection and tracking systems, standard video cameras are used and sometimes with wide angle lenses. For enhancing the robustness and accuracy of the detection system through sensor fusion, they are integrated as a part of multi sensor setups, such as thermal and fisheye cameras (18, 22).

Types of sensors in drones

These drones are sound detectable, they shall be identified by acoustic sensors adding the possibility of other type of sensors (18). For real-time anomaly inspection in drones, the MEMS (micro electromechanical system) accelerometers are used, like ADXL335 and ADXL345. They are good in identifying faulty conditions which may not be visible to one's naked eyes (23). For indoor positioning, the positioning is done through inertial measurement units and sonar sensor that give the orientation and distance of drones to objects (24). Simultaneous localization and mapping are the purposes of these, especially because it helps drones to navigate in a complicated environment by creating a replica of its surrounding (24). The indoor drone positioning provided by UWB sensors is realized by triangulating the drone location using multiple anchors (24). Long distance detection is done and against weather conditions, the frequency modulated continuing wave (FMCW) radar sensors are robust. For comprehensive area coverage, they belong to the sensor networks (25). Located on the drone, these sensors provide high coordinates accuracy in 3D space for the drone landing and take-off, without even relying on the GPS (26). Passive radio frequency imaging has SDR sensors that offer continuous coverage on top of intelligent anti-drone systems (27). Various types of sensors are compiled in Table 3.

Application of drone technology in forestry

Drones are cheap and flexible platform for remote sensing and data collection to fill the data gaps left by other remote sensing methods, such as manned aircraft and satellites (1, 3). Drones are used for surveying forests, mapping canopy gaps, measuring canopy height, tracking wildfires. With the increasing use of UAVs for monitoring the forest health, they offer high spatial, repetitive and timely data which is critical for specifying forest health. This is especially relevant to detecting biotic or abiotic stressor affecting forests (5). Drones aid forest management in creating canopy height model, mapping forest gaps, as well as intensive management. Also, they are used in inventorying the resources, mapping the diseases and fire effects (2, 3). Small drones are low cost and detail the monitoring of forests; they are feasible for community-based forest monitoring. This approach helps local management and conservation efforts especially in tropical areas (9). Its potential uses according to its types has been gathered in Table 4 and 5.

Applications of drones in forest monitoring

However, considering that drones deliver low-cost data of a high resolution, they can enhance gathering canopy variables and assist biodiversity assessment (28). Recce UAVs are used to capture high resolution images of forest health to monitor physiological stress in trees even in early stages of disease outbreak (4, 5). However, they are especially useful for evaluating individual tree health and pattern of mortality (29). For example, small drones are a feasible tool for community-based forest monitoring and provide data on details of forest loss, degradation and regrowth - essential for REDD+ activities (9). Continuous surveillance of forests using drones for the purpose of detecting changes like encroachment or fires helps in conservation and maximizing the response time (10) (Fig. 2). Table 6 covers the major issues faced when drones are used for forest monitoring.

Applications in forest biometrics

With photogrammetry and structure from motion techniques, drones make it possible to map individual trees to build 3D models of forest stands. This method offers one of the advantages: speed, as it is particularly helpful in structurally complex forests, for which the traditional methods could fail

Table 3. UAV sensor technologies used in forestry

Sensor type	Spectral range	Application in forestry	Example UAV model	Reference
RGB Camera	Visible	General Mapping, Tree Counting	DJI Phantom 4 Pro	(19)
Multispectral	VNIR	Vegetation Health, Pest Detection	Parrot Sequoia	(17)
Hyperspectral	VNIR-SWIR	Species Classification, Disease Monitoring	Headwall Nano-Hyperspectral	(18)
LiDAR	Active (Laser)	Canopy Structure, Biomass Estimation	DJI Matrice 600 with LiDAR	(19)

Table 4. Applications of drones in forestry

Application	Description	Benefits
Forest mapping	Creating detailed maps of forest areas	Saves time, cost, labour
Precision forestry	Assessing forest parameters like canopy cover and tree volume	Improves decision-making for forest management
Canopy gap mapping	Identifying gaps in the forest canopy	Provides insights into forest disturbances
Forest health monitoring	Detecting pest infestations and assessing forest vitality	Early detection of problems, saves time and money
Measuring forest canopy height	Determining canopy height using LiDAR or other sensors	More efficient and cost-effective than traditional methods

Table 5. UAV types and their applications in forestry

UAV type	Primary application	Advantage	Limitation	Reference
Fixed-wing	Large Area Mapping, Biomass Estimation	High coverage per flight	Requires large take off/ landing space	(20)
Rotary-wing	Forest Health Monitoring, Tree Species Classification	High manoeuvrability, detailed imaging	Limited flight duration	(18)
Hybrid (VTOL)	Mixed Applications (Mapping & Monitoring)	Combines benefits of fixed & rotary-wing UAVs	More complex technology, costlier	(19)

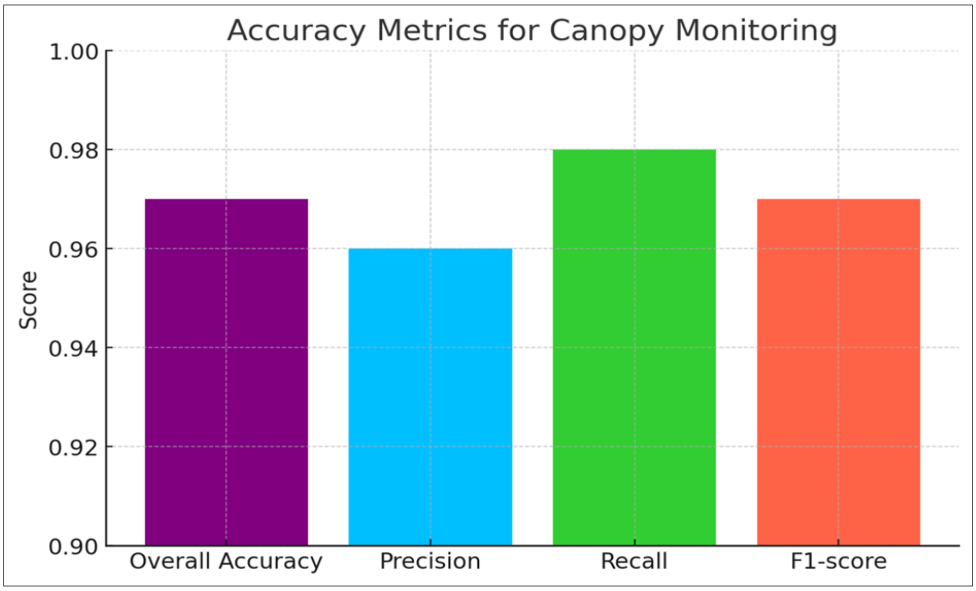

Fig. 2. Precision and overall performance of drones in canopy monitoring.

(30, 31). Drones have also been used to differentially identify canopy and understory trees. To discriminate these sites, it is necessary to differentiate these sites (31) (Fig. 3).

Drones in precision forestry

These are a relatively low-cost alternative to maned aircraft and satellite systems and they have high degrees of flexibility in the control over spatial and temporal resolution (1, 3). Drones are robots are ideal for collecting highly concentrated data without human crew risk, while it has been also mentioned that robots are a perfect fit for such high degree data collection (1, 3). Drones can easily fill these data gaps quickly and relatively inexpensively if they are able to collect high resolution imagery quickly and at a relatively low cost. This can enable such applications as for forest mapping, canopy height measurement or wildfire tracking (1, 3). As UAVs are very recently 'adopted' as an analysis tool for forest health monitoring purposes due to the rapid and repetitive acquisition of high-resolution data, the importance of UAV use for augmentation is significant. It is essential that such biotic and abiotic stressors affecting forest health are detected (5). Precision seeding using drones includes targeting microsites to improve success rate of seed establishment and decrease costs. This approach is more efficient than existing blanket seeding methods (32) (Fig. 4).

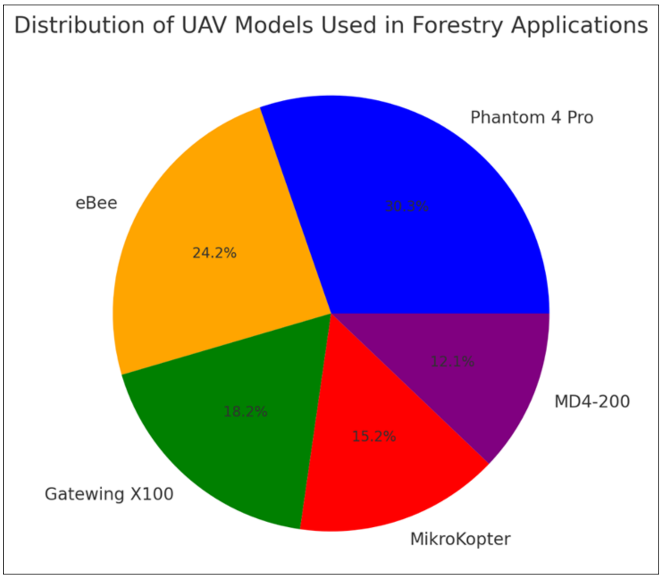

Fig. 3. Abundance of various UAV's used in forestry.

Table 6. Key disadvantages of a drone-assisted community-based forest monitoring approach

Issue	Description
Small payload	Limits the quality of imaging sensors
Low spectral resolution	High costs of high spectral-resolution sensors
Poor geometric and radiometric performance	Affects the possibility of accurately georeferencing the imagery acquired
Low software automation	Complex analyses can be done faster by organizations and end-users
Sensitivity to atmospheric conditions	Fog, heavy rain and strong and variable winds can hinder their operation
Short flight endurance	Should not be a major constraint for CBFM unless a community's territory is very large
Possibility of collisions	Poses a significant risk to small drones and warrant the need for training and acquiring expertise on flight path setting and manual manoeuvring when needed
Potential problems for repairs and maintenance	May significantly increase the operating cost and loss of flying time
Dependence on external assistance and funding	Communities would be very dependent on initial training and continued funding from partner organizations or government agencies
Ambiguous or cumbersome regulations for flying small drones	Impede their use, particularly in the case of non-commercial models
Safety and security issues	May pose significant threats to the security of the drone operators, other community members and even the partner organizations' personnel involved in the CBFM program
Debatable relevance for community conservation and socio-economic development	Would not be relevant and could be antagonistic for communities that do not want to engage in externally driven conservation programs and development projects on ideological grounds
Potential social impacts	Drone technology usage might lead to community segmentation by widening the knowledge gap amongst technology users and other community members (younger/ older, male/female) and by altering the existing internal power dynamics
Ethical issues	The most immediate ethical concern is the possibility of privacy violations and the requirements for free, prior and informed consent (FPIC)

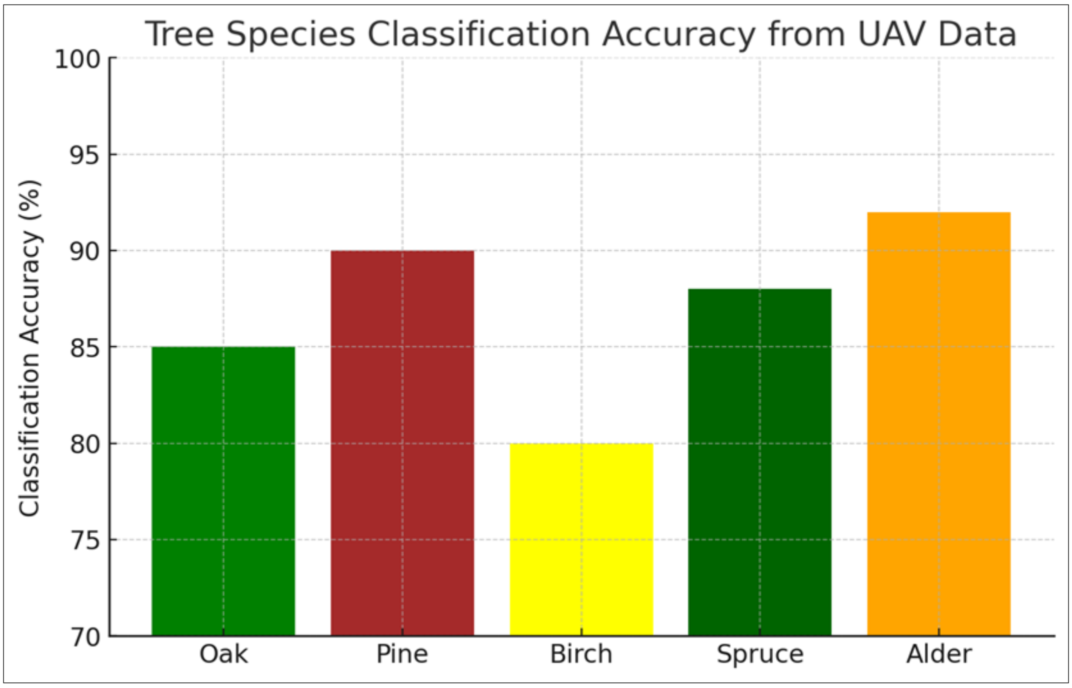

Fig. 4. Accuracy of tree species differentiation through drones.

Benefits of drones in forest conservation and biodiversity monitoring

With high resolution cameras, drones have the added capability of taking detailed photos and data to do precise mapping of the ecosystems, evaluation of canopy health and to observe distributions and biodiversity of species (7, 29). They can enter difficult areas, or those dangerous such as when hit by natural disasters, without endangering people. The capability described here is particularly useful for the monitoring of remote or hazardous sites (10, 33). Information from the data collected by drones can lead to a better decision by forest managers about the forest dynamics, species interactions and effects of changes on the environment (7, 9, 28) (Fig. 5 and 6).

Usage of drones in forest fire

Capturing the images in real time, drones equipped with optical cameras and CNNs offer a reliable system for early fire detection. Due to this system space authority can be informed by this system with alert along with detailed information about fire's location and regional conditions, making the fire detection more efficient and precise (34). Furthermore, drones that are fitted with thermal imaging cameras can recognize fires and send the data to rescue officers and the image also has a wide viewing angle and real time streaming to smartphones (35). With that in mind, drones not only detect but also have a strong role in fire suppression. They have developed systems to drop the fire extinguishing bomb inside the fire zones to extinguish the fire at a low cost and rapidly.

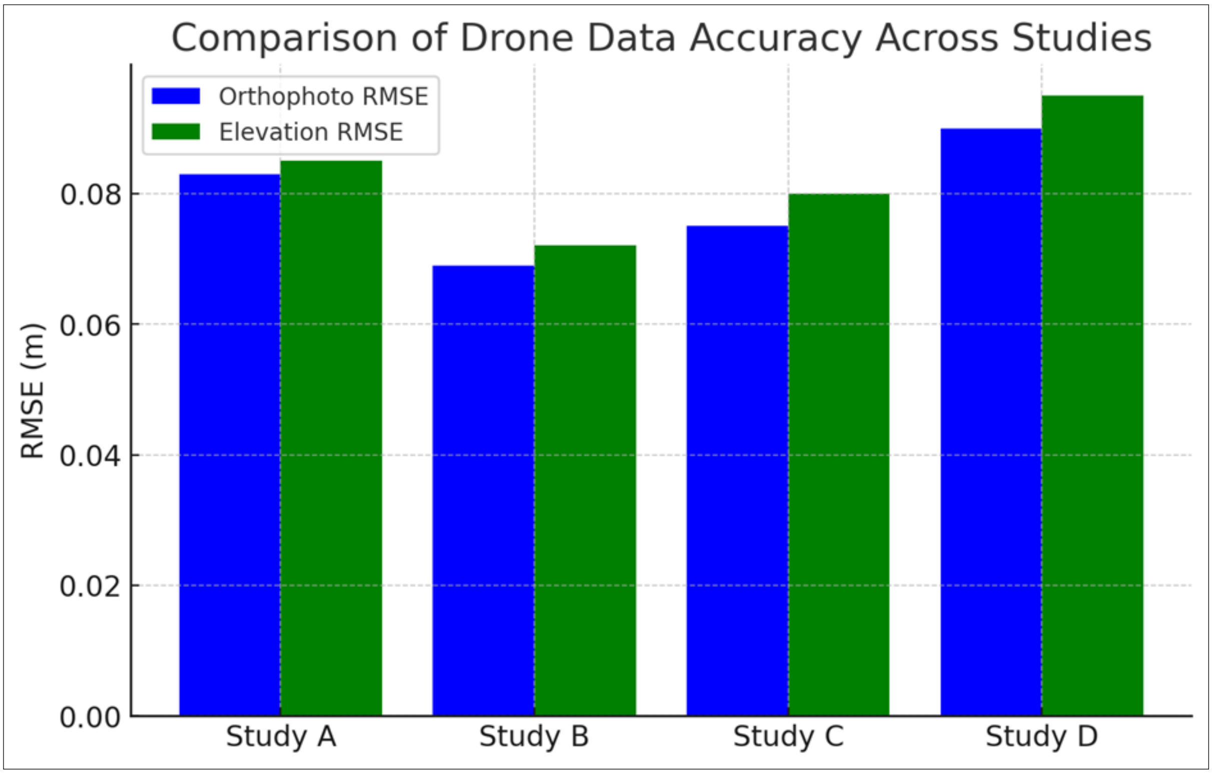

Fig. 5. Comparison between orthophoto and elevation calculated through UAV's.

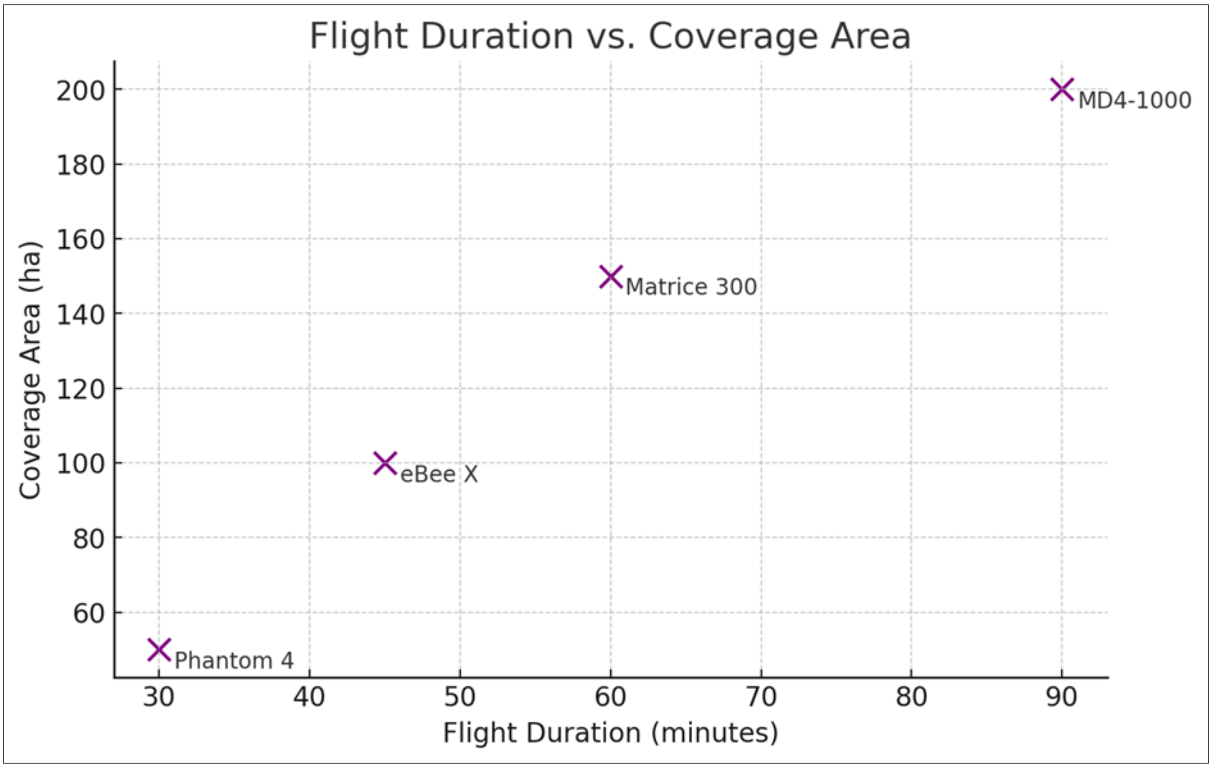

Fig. 6. Comparison between flight duration within different types of UAV's.

Vertical towers supply these drones with extinguishing materials so as these drones can conduct a continuous and repeated fire suppression efforts (8). In addition, drone swarms can produce a continuous flow of liquid for extinguishing, thereby creating 'rain' over the area that has caught fire-all machines can work simultaneously and this is thought to be highly effective on low intensity burns (36). This is especially important for managing drones with blockchain technology, as they are involved in firefighting operations and are operated in remote regions that have yet to be developed. Such an integration (8) enables a smooth exchange of data as well as alleviates challenges pertaining to the spatial distances between a system and its dependent systems. In addition, drones may utilize swarm intelligence and nature inspired algorithms to autonomously detect and extinguish distributed (concentrated in space as opposed to time) fire spots from any given location that optimizes coverage of the area and energy consumption (37). Various types of drones and their application with respect forest fire is mentioned in Table 7.

Wildlife monitoring and habitat assessment through drones

Drones help in conservation management in protected areas in a costless and novel way. Operational and analytical challenges remain but they are used for wildlife monitoring, ecosystem assessment and even for law enforcement (38). Rapid and extensive coverage of large areas and the ability to collect highly accurate and precise data often beyond the capacity of human observers, also enables them to provide high quality data, in some cases of higher accuracy or precision (39). This comes from machine learning algorithms integrated with drones for the semi or complete automated detection of wildlife, like it is faster and sometimes more accurate than manual evaluation (39, 40). The development of sophisticated methods of wildlife monitoring is now made possible due to recent advancements of drone technology and machine learning. For example, the SE-YOLO model that contains channel self-attention mechanism is one of the model performances that can detect small wildlife targets in drone imagery (41). Additionally, our findings are in line with previous studies, where thermal infrared (TIR) cameras equipped on drones are used as a reliable source of observation of species in unproductive forested areas for ungulates (42).

Early detection of invasive species using UAVs

In the past studies have used machine learning algorithms such random forests, neural networks and support vector machines to classify and detect invasive species out of the multi and hyperspectral data acquired from UAV (43). These methods were able to identify high rates of the invasive species phragmites australis and *Dendroctonus valens* as the source said spectral and hyperspectral sensors fitted to dual camera of the UAVs can be used to differentiate the invasive species from the existing vegetation (4).

Applications of multispectral drones in forestry

In fact, multispectral drones can specially detect physiological stress of trees caused by biotic and abiotic factors. At the tree level, they can perceive stress and not satellite values (4, 5, 44), while they will pick up on stress in clusters of trees, as opposed to the tree level. Such multispectral sensors can be provided in drones to make high accurate tree species measurement and

Table 7. UAV-based forest fire detection systems

UAV Model	Type	Sensor Used	Application	Reference
DJI Matrice 210 RTK	Rotary-Wing	IR Camera (XT) & RGB (X5S)	Real-time Fire Detection, Smoke Analysis	(22)
ALTi Transition VTOL	Hybrid	EO/IR Camera	Long-Term Monitoring, Thermal Analysis	(22)
DJI Matrice 600 Pro	Rotary-Wing	Dual Sensor	Close Inspection, Fire Perimeter Assessment	(33)

classification with classification of biomass estimation. To get the detailed spectral data from the drones, advanced machine learning algorithms such as deep neural networks are used (45). For instance, Multispectral drones can be used to conduct surveys of very large and heterogeneous areas that were destroyed by things like fires to assess their recovery, such as vegetation. The imagery obtained from such imagery has much higher spatial detail than imagery from satellite imagery (46). Multispectral data combined with drone's 3D point clouds effectively classifies and evaluates the intensity of insect damage in trees by the vertical distribution inside a tree (6) (Fig. 7).

Applications of drone swarms in forestry

Drone swarms can be deployed to extinguish a wildfire by resembling rain, by constantly delivering a constant flow of extinguishing liquid to fight the wildfire. It is most effective on low intensity fires and can work with existing firefighting methods (8, 43, 44). Real time detection and monitoring of wildfires is achieved using swarms. What they achieve is continuous telemetry and mapping to assist in studying tactical plans, cutting costs with better resource allocation (46, 47). Drones' swarms using advanced algorithms can autonomously detect and extinguish fire spots, find their paths based on utilizing their fire extinguishing coverage and energy consumption with calculative values as much as possible (48). Dense forests are prone to being plagued with unauthorised human presence and drones themselves would be unable to identify these anomalies due to their scale and complexity, but ultra-high efficiency, ultra-high speed swarms of drones equipped with advanced imaging technologies can be utilised and programmed to search for and track anomalies. The capability of detecting humans is vital for security operations and for environmental monitoring (49, 50). Swarms of autonomous drones can autonomously plan and execute their traversals of the complex forest environments, plan their obstacle avoidance, coordination between swarm drones that maintain efficiency and safety (50, 51). The operations of several drones working in a swarm should be organized by sophisticated algorithms to enable effective coordination and reduce the cognitive load on the human operators (52, 53). In remote forest areas, energy use and resource usage are critical for prolonged operation of drone swarms (54).

Current legal framework about drones in India

In India, the drone operations are primarily overseen by the Directorate General of Civil Aviation (DGCA). There are Civil Aviation Requirements (CAR) guidelines by the DGCA that addresses the operational restrictions, documentation requirement and zones designated for the use of drones. The purpose of these guidelines is to fulfil the march of technology keeping in view the safety, privacy and national security concerns (55, 56). However, there are yet several challenges that persist. In India UAVs regulations are spaced according to the air space, there are three fly zones namely green zone (no permission required up to 400ft), yellow zone (permission required i.e., areas within 8-12 km of airports) and red zone (no fly zone) (56, 57). The industry growth has outpaced the current legal structures as all the big players are racing to get in on the drone market and they are finding holes in the policy. Some of the significant concerns are still issues like safety, privacy and data protection. Furthermore, national and international regulation is not harmonized which makes cross border drone operations difficult (58). Its drone regulations are compared to those of other countries in need of a unified global framework. With such a framework, it would standardize practice, promote collaboration across borders and enable the safe and effective use of drones across the globe (58, 59).

Challenges and considerations in implementing drone technology in forestry

Currently, the full potential of UAVs in forestry applications is restrained due to the lack of using advanced sensors such as hyperspectral and LiDAR (5, 7). Commercial software, that is

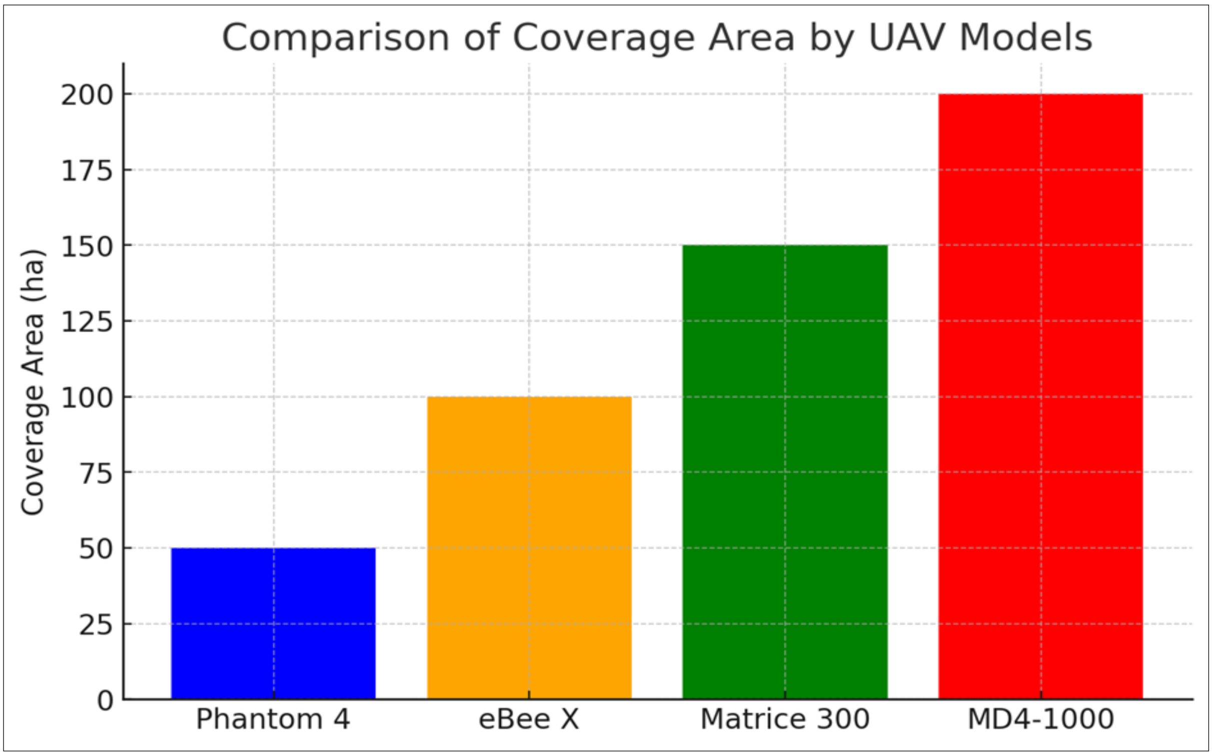

Fig. 7. Area covered by various UAV's in a single flight.

being relied on for data processing presents a barrier to the use of open-source tools that can improve flexibilities and accessibility of data such as the GitHub (19). Standardized workspace is not shared, which results in an inconsistent use of data collection and analysis, influencing the reliability of results (19). Weather conditions and challenging terrains can limit UAV operations from carrying out data acquisition and influencing operational efficiency (60). Challenges of UAV supported forest regeneration are low (seed) survival rate and future forest diversity. UAVs furthermore have low operational costs; however, their initial setup and maintenance are still cost intensive, particularly in case of community-based monitoring programs (30). While traditional methods of planting by hand may help to maintain the emotional and cultural links of people to the land, the use of drones will serve to sever these ties (34).

Conclusion

This seminar paper gave a complete review of the current use and prospects of drone technology in the forestry by highlighting advantages and disadvantages of the technology. Now, drones are being used for a variety of purposes such as mapping, precision forestry, forest heath monitoring and post fire recovery. Application of drones in forestry has great potential for revolutionising how traditional forestry practices have been done in that it offers accurate and timely data, reduced the cost and makes this process efficient. Finally, with projecting far ahead, drone technology in forestry seems to be a promising prospect. Machine learning, deep learning and energy harvesting advancement are expected to increase the capability of drones so that there will be smarter and more efficient, drones capable of autonomous intensive tasks. Novel antenna designs will be developed and aerial blockchain technology integrated to further improve communication, security, data integrity in drone forestry operation. Besides, with ease in accessibility and affordability of drones and the advancement of user-friendly software with standardized regulations, drone use in the forestry sector is now on the rise. With the advancements of the drone technology, its application is predicted to be extended to more areas of the forestry fields including forest dynamics, species detection and forest disturbance evaluation.

Acknowledgements

I would like to thank my chairman, Dr. R. Ravi, for guiding me throughout the process. I am also grateful to the Forest College and Research Institute for providing me with all the facilities I needed.

Authors' contributions

RR helped choose the review topic and its outline. KB contributed ideas related to the topic and drafted the manuscript. KPR corrected my remote sensing-related points. MV me helped with AI-related work. PH participated in the sequence alignment. AH and SS helped with the overall correction of the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

References

1. Tang L, Shao G. Drone remote sensing for forestry research and practices. J For Res. 2015;26:791-7. https://doi.org/10.1007/s11676-015-0088-y
2. Torresan C, Berton A, Carotenuto F, Di Gennaro SF, Gioli B, Matese A, et al. Forestry applications of UAVs in Europe: a review. Int J Remote Sens. 2017;38(8-10):2427-47. https://doi.org/10.1080/01431161.2016.1252477
3. Banu TP, Borlea GF, Banu C. The use of drones in forestry. J Environ Sci Eng B. 2016;5(11):557-62. https://doi.org/10.17265/2162-5263/2016.11.007
4. Dash JP, Watt MS, Paul TS, Morgenroth J, Pearse GD. Early detection of invasive exotic trees using UAV and manned aircraft multispectral and LiDAR data. Remote Sens. 2019;11 (15):1812. https://doi.org/10.3390/rs11151812
5. Ecke S, Dempewolf J, Frey J, Schwaller A, Endres E, Klemmt HJ, et al. UAV-based forest health monitoring: a systematic review. Remote Sens. 2022;14(13):3205. https://doi.org/10.3390/rs14133205
6. Shrestha A, Hicke JA, Meddens AJ, Karl JW, Stahl AT. Evaluating a novel approach to detect the vertical structure of insect damage in trees using multispectral and three-dimensional data from drone imagery in the Northern Rocky Mountains, USA. Remote Sens. 2024;16(8):1365. https://doi.org/10.3390/rs16081365
7. Díaz-Delgado R, Mücher S. Editorial of special issue "Drones for biodiversity conservation and ecological monitoring". Drones. 2019;3(2):47. https://doi.org/10.3390/drones3020047
8. Ausonio E, Bagnerini P, Ghio M. Drone swarms in fire suppression activities: a conceptual framework. Drones. 2021;5(1):17. https://doi.org/10.3390/drones5010017
9. Paneque-Gálvez J, McCall MK, Napoletano BM, Wich SA, Koh LP. Small drones for community-based forest monitoring: an assessment of their feasibility and potential in tropical areas. Forests. 2014;5(6):1481-507. https://doi.org/10.3390/f5061481
10. Melhim LK, Jemmali M, Boulila W, Alazab M, Rani S, Campbell H, et al. Leveraging drone-assisted surveillance for effective forest conservation: a case study in Australia's Daintree Rainforest. IEEE Internet Things J. 2024;11(19):31167-79. https://doi.org/10.1109/JIOT.2024.3419710
11. Okulski M, Ławryńczuk M. A small UAV optimized for efficient long-range and VTOL missions: an experimental tandem-wing quadplane drone. Appl Sci. 2022;12(14):7059. https://doi.org/10.3390/app12147059
12. Shraim H, Awada A, Youness R. A survey on quadrotors: configurations, modeling and identification, control, collision avoidance, fault diagnosis and tolerant control. IEEE Aerosp Electron Syst Mag. 2018;33(7):14-33. https://doi.org/10.1109/MAES.2018.160246
13. Khan W, Nahon M. Toward an accurate physics-based UAV thruster model. IEEE/ASME Trans Mechatron. 2013;18(4):1269 -79. https://doi.org/10.1109/TMECH.2013.2264105
14. Guan YJ, Li YP. Design and aerodynamic characteristics analysis of propellers for a novel rescue unmanned aerial vehicle. Aircr Eng Aerosp Technol. 2024;96(1):162-74. https://doi.org/10.1108/AEAT-11-2022-0327

15. Ryll M, Bülthoff HH, Giordano PR. A novel overactuated quadrotor unmanned aerial vehicle: modeling, control and experimental validation. IEEE Trans Control Syst Technol. 2014;23(2):540-56. https://doi.org/10.1109/TCST.2014.2330999

16. Ichiro Ishimaru. Extremely compact hyperspectral camera for drone and smartphone. Proc Int Workshop Image Sens Imaging Syst. 2016;1:264-7.

17. Meng L, Hirayama T, Oyanagi S. Underwater-drone with panoramic camera for automatic fish recognition based on deep learning. IEEE Access. 2018;6:17880-6. https://doi.org/10.1109/ACCESS.2018.2820326

18. Svanström F, Alonso-Fernandez F, Englund C. Drone detection and tracking in real-time by fusion of different sensing modalities. Drones. 2022;6(11):317. https://doi.org/10.3390/drones6110317

19. Falanga D, Kleber K, Scaramuzza D. Dynamic obstacle avoidance for quadrotors with event cameras. Sci Robot. 2020;5(40):eaaz9712. https://doi.org/10.1126/scirobotics.aaz9712

20. Alexovič S, Lacko M, Bačík J. 3D mapping with a drone equipped with a depth camera in indoor environment. Acta Electrotech Inform. 2023;23(1):18-24. https://doi.org/10.2478/aei-2023-0003

21. Larsen HL, Møller-Lassesen K, Enevoldsen EM, Madsen SB, Obsen MT, Povlsen P, et al. Drone with mounted thermal infrared cameras for monitoring terrestrial mammals. Drones. 2023;7(11):680. https://doi.org/10.3390/drones7110680

22. Unlu E, Zenou E, Riviere N, Dupouy PE. Deep learning-based strategies for the detection and tracking of drones using several cameras. IPSJ Trans Comput Vis Appl. 2019;11:1-3. https://doi.org/10.1186/s41074-019-0059-x

23. Ghazali MH, Rahiman W. An investigation of the reliability of different types of sensors in the real-time vibration-based anomaly inspection in drone. Sensors. 2022;22(16):6015. https://doi.org/10.3390/s22166015

24. Vanhie-Van Gerwen J, Geebelen K, Wan J, Joseph W, Hoebeke J, De Poorter E. Indoor drone positioning: accuracy and cost trade-off for sensor fusion. IEEE Trans Veh Technol. 2021;71(1):961-74. http://doi.org/10.1109/TVT.2021.3129917

25. Coluccia A, Parisi G, Fascista A. Detection and classification of multirotor drones in radar sensor networks: a review. Sensors. 2020;20(15):4172. https://doi.org/10.3390/s20154172

26. Averin D, Borovytsky V. Coordinate measurement in multi-beam drone positioning system. Visn Ternopil Nac Tech Univ. 2023;109(1):80-9. https://doi.org/10.33108/visnyk_tntu2023.01.080

27. Flak P. Drone detection sensor with continuous 2.4 GHz ISM band coverage based on cost-effective SDR platform. IEEE Access. 2021;9:114574-86. https://doi.org/10.1109/ACCESS.2021.3104738

28. hang J, Hu J, Lian J, Fan Z, Ouyang X, Ye W. Seeing the forest from drones: testing the potential of lightweight drones as a tool for long-term forest monitoring. Biol Conserv. 2016;198:60-9. https://doi.org/10.1016/j.biocon.2016.03.027

29. Harris RC, Kennedy LM, Pingel TJ, Thomas VA. Assessment of canopy health with drone-based orthoimagery in a Southern Appalachian red spruce forest. Remote Sens. 2022;14(6):1341. https://doi.org/10.3390/rs14061341

30. Young DJ, Koontz MJ, Weeks J. Optimizing aerial imagery collection and processing parameters for drone-based individual tree mapping in structurally complex conifer forests. Methods Ecol Evol. 2022;13(7):1447-63. https://doi.org/10.1111/2041-210X.13860

31. Araujo RF, Chambers JQ, Celes CH, Muller-Landau HC, Santos AP, Emmert F, et al. Integrating high resolution drone imagery and forest inventory to distinguish canopy and understory trees and quantify their contributions to forest structure and dynamics. PLoS One. 2020;15(12):e0243079. https://doi.org/10.1371/journal.pone.0243079

32. Castro J, Alcaraz-Segura D, Baltzer JL, Amorós L, Morales-Rueda F, Tabik S. Automated precise seeding with drones and artificial intelligence: a workflow. Restor Ecol. 2024;32(5):e14164. https://doi.org/10.1111/rec.14164

33. Coldrey JJ, Thompson BS. Evaluating stakeholder perceptions on drone use in forest restoration using a social–ecological systems framework. People Nat. 2024;6(4):1624-39. https://doi.org/10.1002/pan3.10660

34. Nayak VY, Rao VG, Jagruthi H. Drones in forest fire mitigation. In: 2023 3rd Int Conf Electr Comput Commun Mechatron Eng (ICECCME). IEEE; 2023. p. 1-7. https://doi.org/10.1109/ICECCME57830.2023.10252566

35. Kinaneva D, Hristov G, Raychev J, Zahariev P. Early forest fire detection using drones and artificial intelligence. In: 2019 42nd Int Conv Inf Commun Technol Electron Microelectron (MIPRO). IEEE; 2019. p.1060-5. https://doi.org/10.23919/MIPRO.2019.8756696

36. Mahmudnia D, Arashpour M, Bai Y, Feng H. Drones and blockchain integration to manage forest fires in remote regions. Drones. 2022;6(11):331. https://doi.org/10.3390/drones6110331

37. Alsammak IL, Mahmoud MA, Aris H, AlKilabi M, Mahdi MN. The use of swarms of unmanned aerial vehicles in mitigating area coverage challenges of forest-fire-extinguishing activities: a systematic literature review. Forests. 2022;13(5):811. https://doi.org/10.3390/f13050811

38. Jiménez López J, Mulero-Pázmány M. Drones for conservation in protected areas: present and future. Drones. 2019;3(1):10. https://doi.org/10.3390/drones3010010

39. Corcoran E, Winsen M, Sudholz A, Hamilton G. Automated detection of wildlife using drones: synthesis, opportunities and constraints. Methods Ecol Evol. 2021;12(6):1103-14. https://doi.org/10.1111/2041-210X.13581

40. Lyons MB, Brandis KJ, Murray NJ, Wilshire JH, McCann JA, Kingsford RT, et al. Monitoring large and complex wildlife aggregations with drones. Methods Ecol Evol. 2019;10(7):1024-35. https://doi.org/10.1111/2041-210X.13194

41. Mou C, Liu T, Zhu C, Cui X. Waid: A large-scale dataset for wildlife detection with drones. Appl Sci. 2023;13(18):10397. https://doi.org/10.3390/app131810397

42. Witczuk J, Pagacz S, Zmarz A, Cypel M. Exploring the feasibility of unmanned aerial vehicles and thermal imaging for ungulate surveys in forests-preliminary results. Int J Remote Sens. 2018;39(15–16):5504–21. https://doi.org/10.1080/01431161.2017.1390621

43. Abeysinghe T, Simic Milas A, Arend K, Hohman B, Reil P, Gregory A, et al. Mapping invasive *Phragmites australis* in the Old Woman Creek estuary using UAV remote sensing and machine learning classifiers. Remote Sens. 2019;11(11):1380. https://doi.org/10.3390/rs11111380

44. Fraser BT, Congalton RG. Monitoring fine-scale forest health using unmanned aerial systems (UAS) multispectral models. Remote Sens. 2021;13(23):4873. https://doi.org/10.3390/rs13234873

45. Nezami S, Khoramshahi E, Nevalainen O, Pölönen I, Honkavaara E. Tree species classification of drone hyperspectral and RGB imagery with deep learning convolutional neural networks. Remote Sens. 2020;12(7):1070. https://doi.org/10.3390/rs12071070

46. Fernández-Guisuraga JM, Sanz-Ablanedo E, Suárez-Seoane S, Calvo L. Using unmanned aerial vehicles in postfire vegetation survey campaigns through large and

heterogeneous areas: opportunities and challenges. Sensors. 2018;18(2):586. https://doi.org/10.3390/s18020586

47. Moghadasi N, Kulkarni A, Crayton D, Grissom R, Lambert JH, Feng L. Formal methods in unmanned aerial vehicle swarm control for wildfire detection and monitoring. In: 2023 IEEE Int Syst Conf (SysCon); 2023. p. 1-8. https://doi.org/10.1109/SysCon53073.2023.10131075
48. Yan X, Chen R. Application strategy of unmanned aerial vehicle swarms in forest fire detection based on the fusion of particle swarm optimization and artificial bee colony algorithm. Appl Sci. 2024;14(11):4937. https://doi.org/10.3390/app14114937
49. Priya A, Kumar S, Kumar S. Surveillance using 5G based drone swarm system for forest area. In: 2024 IEEE Students Conf Eng Syst (SCES); 2024. p. 1–5. https://doi.org/10.1109/SCES61914.2024.10652563
50. Nathan RJ, Strand S, Mehrwald D, Shutin D, Bimber O. An autonomous drone swarm for detecting and tracking anomalies among dense vegetation. arXiv. 2024. https://doi.org/10.48550/arXiv.2407.10754
51. Zhou X, Wen X, Wang Z, Gao Y, Li H, Wang Q, et al. Swarm of micro flying robots in the wild. Sci Robot. 2022;7(66):eabm5954. https://doi.org/10.1126/scirobotics.abm5954
52. Bjurling O, Granlund R, Alfredson J, Arvola M, Ziemke T. Drone swarms in forest firefighting: a local development case study of multi-level human-swarm interaction. In: Proc 11th Nordic Conf Human-Computer Interaction; 2020. p. 1–7. https://doi.org/10.1145/3419249.3421239
53. Roldán-Gómez JJ, González-Gironda E, Barrientos A. A survey on robotic technologies for forest firefighting: Applying drone swarms to improve firefighters' efficiency and safety. Appl Sci. 2021;11(1):363. https://doi.org/10.3390/app11010363
54. Alsammak IL, Mahmoud MA, Gunasekaran SS, Ahmed AN, AlKilabi M. Nature-inspired drone swarming for wildfires suppression considering distributed fire spots and energy consumption. IEEE Access. 2023;11:50962–83. https://doi.org/10.1109/ACCESS.2023.3279416
55. Singh P, Shahi V. Laws related to use of drone in India-A critical analysis. DME J Law. 2024;5(1):12–7. https://doi.org/10.53361/dmejl.v5i01.02
56. Srivastava S, Gupta S, Dikshit O, Nair S. A review of UAV regulations and policies in India. In: Proc UASG 2019: Unmanned aerial system in geomatics. Vol. 1. Springer; 2020. p. 315–25. https://doi.org/10.1007/978-3-030-37393-1_27
57. Kim DH. Regulations and laws pertaining to the use of unmanned aircraft systems (UAS) by ICAO, USA, China, Japan, Australia, India and Korea. In: Unmanned aerial vehicles in civilian logistics and supply chain management. Hershey (PA): IGI Global; 2019. p. 169–207. https://doi.org/10.4018/978-1-5225-7900-7.ch007
58. Nugraha RA, Jeyakodi D, Mahem T. Urgency for legal framework on drones: Lessons for Indonesia, India and Thailand. Indones Law Rev. 2016;6:137. https://doi.org/10.15742/ilrev.v6n2.229
59. Dainelli R, Toscano P, Di Gennaro SF, Matese A. Recent advances in unmanned aerial vehicle forest remote sensing-A systematic review. Part I: A general framework. Forests. 2021;12(3):327. https://doi.org/10.3390/f12030327
60. Mohan M, Richardson G, Gopan G, Aghai MM, Bajaj S, Galgamuwa GP, et al. UAV-supported forest regeneration: Current trends, challenges and implications. Remote Sens. 2021;13(13):2596. https://doi.org/10.3390/rs13132596
61. Adoni WY, Lorenz S, Fareedh JS, Gloaguen R, Bussmann M. Classification of uncrewed aerial vehicles. Encyclopedia; 2023. https://encyclopedia.pub/entry/43656

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.