

Emerging Role of Drone Technologies in Environmental Research: Trends, Applications, and Future Directions

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Abstract

Unmanned aerial vehicles (UAVs), commonly called drones, have rapidly transformed environmental research and management over the past decade. Their flexibility, improving sensor payloads, and ability to collect high-resolution spatial and temporal data make them powerful tools across disciplines — from biodiversity monitoring and precision agriculture to water quality assessment and disaster response. UAVs bridge the gap between ground-based surveys and satellite remote sensing by offering near-real-time, fine-scale data acquisition that can be tailored to specific research objectives. The integration of advanced imaging technologies such as multispectral, hyperspectral, LiDAR, and thermal sensors has further expanded their applicability in mapping vegetation health, detecting pollution sources, quantifying erosion, and assessing wildlife habitats. This review synthesizes the state of knowledge on drone platforms and sensors, key environmental applications, data processing pipelines, limitations and challenges (technical, legal, and ethical), and future research directions. We emphasize methodological advances, best practices for study design, and integration of UAV-derived datasets into broader environmental monitoring frameworks. Moreover, we explore the role of artificial intelligence and machine learning in automating image analysis and improving decision-making accuracy. As UAV technology continues to evolve, its potential for supporting sustainable environmental management, enhancing resilience to climate change, and enabling community-based monitoring initiatives grows substantially. Ten representative references are provided to guide further reading.

Keywords: Unmanned aerial vehicles (UAVs), environmental monitoring, remote sensing, drone applications, sustainable resource management

INTRODUCTION

The global environment is undergoing rapid change due to anthropogenic pressures and climate variability. Effective monitoring and management require observations at appropriate scales: fine enough to capture heterogeneity, frequent enough to detect change, and flexible enough to target remote or dangerous locations. Drones bridge gaps between ground-based sampling and satellite remote sensing by providing centimeter-to-decimeter resolution imagery, on-demand deployment, and lower operational costs for many tasks.

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Modern UAV applications span airborne photogrammetry (RGB, multispectral), thermal imaging, LiDAR, hyperspectral sensing, and direct in situ sampling (e.g., air or water samplers). Advances in autopilot systems, battery technology, and open-source autopilots have democratized access to UAVs, while improvements in machine learning for image analysis enable rapid extraction of ecological and environmental metrics [1].

This review organizes the literature and practice into (i) UAV platforms and sensor payloads, (ii) applications across environmental domains, (iii)

data processing and analytics, (iv) constraints and challenges, and (v) future opportunities. Where possible we highlight methodological best practices and considerations for reproducible UAV-based research [2].

UAV PLATFORMS AND SENSOR PAYLOADS

Platform Types

UAVs Used in Environmental Studies Generally Fall into Three Categories:

- *Multirotor (rotary-wing) drones*: highly maneuverable, capable of vertical takeoff and landing (VTOL), ideal for low-altitude surveys, targeted inspections, and hover-based sampling. Typical flight durations are 15–50 minutes depending on payload and battery.
- *Fixed-wing drones*: efficient for long-distance mapping and extended coverage, can cover tens to hundreds of hectares per flight, but require runway/launch/recovery systems or catapults and cannot hover.
- *Hybrid VTOL/Fixed-wing*: combine VTOL convenience with fixed-wing efficiency; increasingly popular for broader coverage with site flexibility.

Choice of platform depends on spatial extent, endurance, payload weight, and the need for station-keeping or detailed vertical observations (Figure 1).

Sensor Payloads

Common Sensors Used in Environmental UAV Work Include:

- *RGB cameras*: high-resolution color imagery for photogrammetry and structure-from-motion (SfM) based orthophotos and digital surface models (DSMs).
- *Multispectral cameras*: capture narrow spectral bands (e.g., NIR, red-edge) useful for vegetation indices (NDVI, EVI), stress detection, and crop monitoring [3].
- *Hyperspectral sensors*: record contiguous spectral bands, enabling material discrimination, species identification, and water quality proxies, though hyperspectral UAVs are heavier and more expensive.
- *Thermal cameras*: measure surface or canopy temperatures, useful for evapotranspiration estimation, animal detection, and leak/heat-loss identification.
- *LiDAR*: active laser scanning for accurate 3D structure retrieval, canopy height models (CHMs), terrain models under vegetation, and biomass estimation.
- *Gas and particulate sensors*: lightweight instruments for measuring air pollutants (CO₂, CH₄, NO_x, PM) when mounted on UAVs; require careful calibration and plume-sampling strategies.
- *Water samplers and sonars*: for direct collection of water samples from inaccessible sites and bathymetric mapping in shallow waters.

Fixed-wing	Rotary-wing		Hybrid-wing
	Helicopter	Multirotor	
Pros: Efficient coverage for large areas, longer flight endurance; Cons: Cannot hover; cannot maintain above ground level (AGL); require open area for take-off and landing.  Crop cam (Air speed 60km/h, flying weight 2.7kg, maximum flying time >30min)	Pros: High efficiency, capable of hovering and close-range inspections; Cons: Mechanically complex  Vapor 55 (Air speed 0--54 km/h, payload weight <10kg, maximum hover time 45min)	Pros: Maneuverability, user-friendly; Cons: Limited flight time, less efficient for extensive area coverage  DJI Phantom 4 (Air speed 0--58 km/h, flying weight 1.4kg, maximum hover time 25min)	Pros: Combines vertical takeoff/landing (VTOL) with fixed-wing efficiency, adaptable to various terrains; Cons: Complexity in design and operation, potentially higher cost.  JOUAV CW -15 (Air speed 0--61 km/h, payload weight <3kg, maximum hover time 180min)

Figure 1. Typical UAV platforms used in environmental studies.

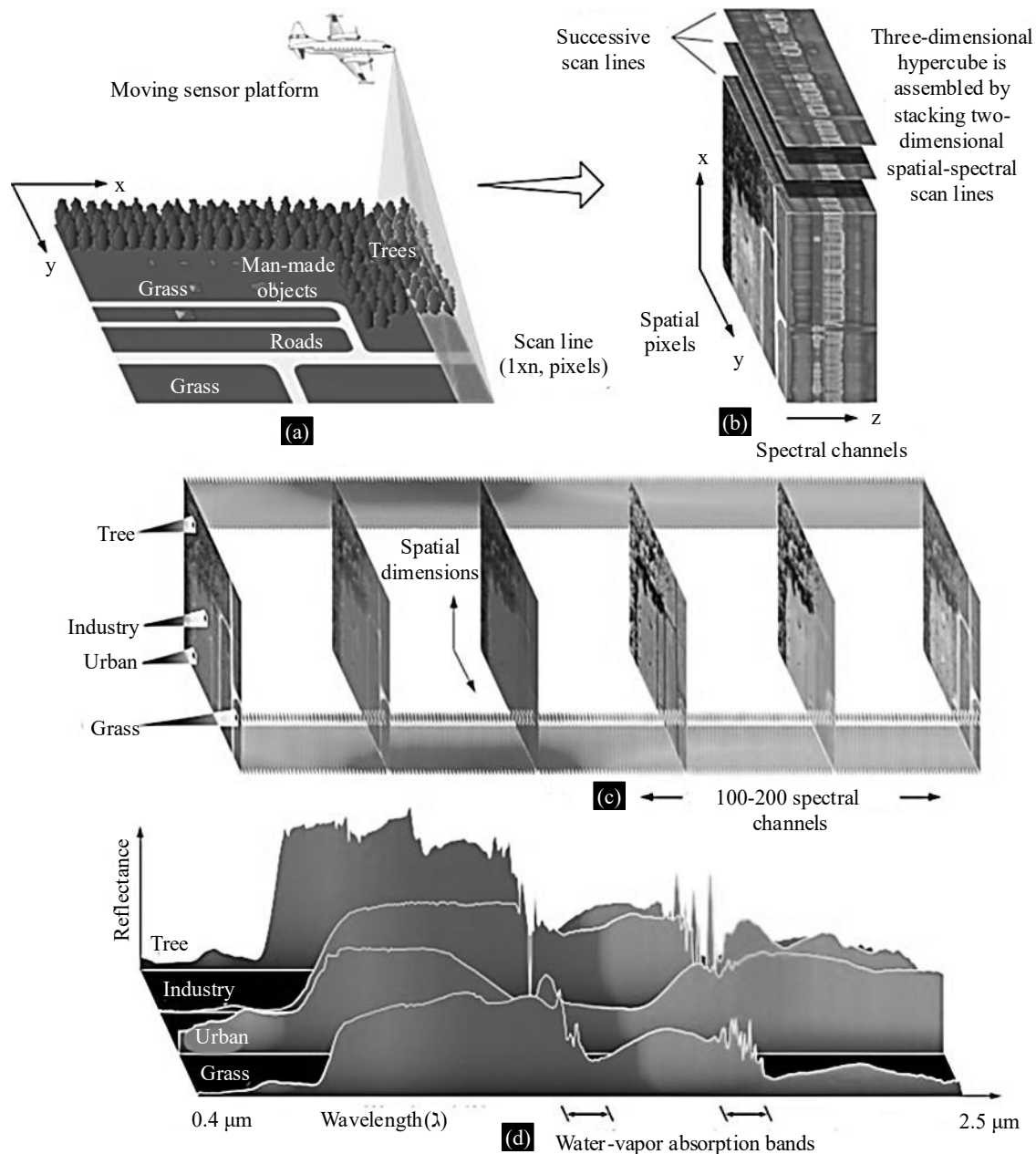


Figure 2. Sensor payloads and their environmental outputs.

Integration and Trade-Offs

Payload weight, power, and data storage constrain sensor choice. Trade-offs exist between spatial resolution, spectral resolution, coverage area, and flight endurance (Figure 2 and 3). For instance, high-resolution hyperspectral sensors drastically increase weight and data volume and typically require larger platforms [4].

KEY ENVIRONMENTAL APPLICATIONS

Vegetation Mapping, Forest Monitoring, and Biomass Estimation

UAVs excel in producing high-resolution orthomosaics and 3D models of vegetation. SfM photogrammetry from overlapping RGB images yields DSMs and digital terrain models (DTMs) after ground control, enabling canopy height estimation when combined with LiDAR or stereo imagery. LiDAR provides precise canopy structure and understorey details, aiding above-ground biomass (AGB) estimation through allometric models or machine learning regressions. Applications include:

- Detecting disease outbreaks and pest infestations through changes in canopy texture and spectral indices.
- Mapping invasive plant species using spectral and structural signatures.
- Post-disturbance assessment (e.g., fire, storm) for burn severity and mortality.

Best practice: combine LiDAR (structure) and multispectral (physiology) data for robust biomass models, and use field plots for calibration and validation.

Precision Agriculture and Crop Health Monitoring

Drones enable frequent monitoring of crop vigor, water stress, and nutrient deficiencies. Multispectral sensors allow computation of vegetation indices (NDVI, NDRE) that correlate with biomass, chlorophyll content, and yield potential. Thermal imaging identifies irrigation inefficiencies via plant canopy temperature anomalies. UAVs guide site-specific management: variable-rate fertilization, targeted pesticide application, and early pest/disease intervention [5].

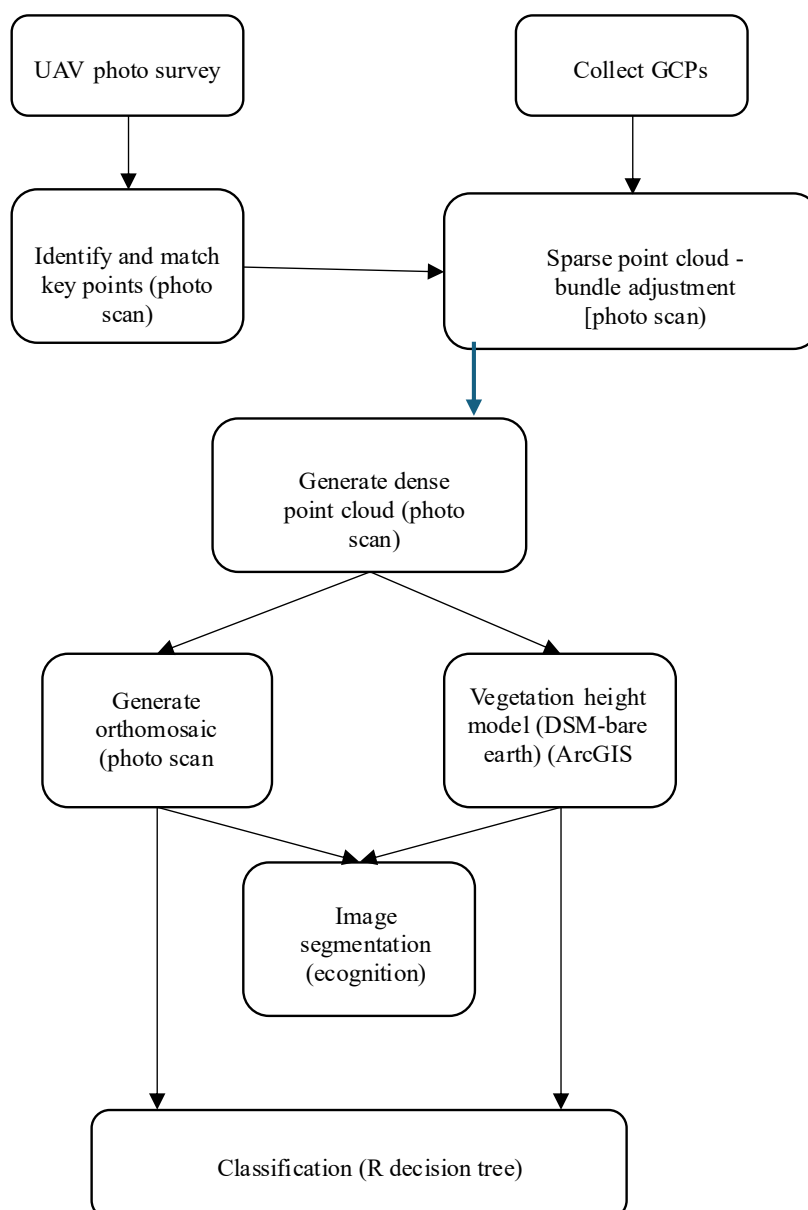


Figure 3. Example UAV workflow for vegetation monitoring.

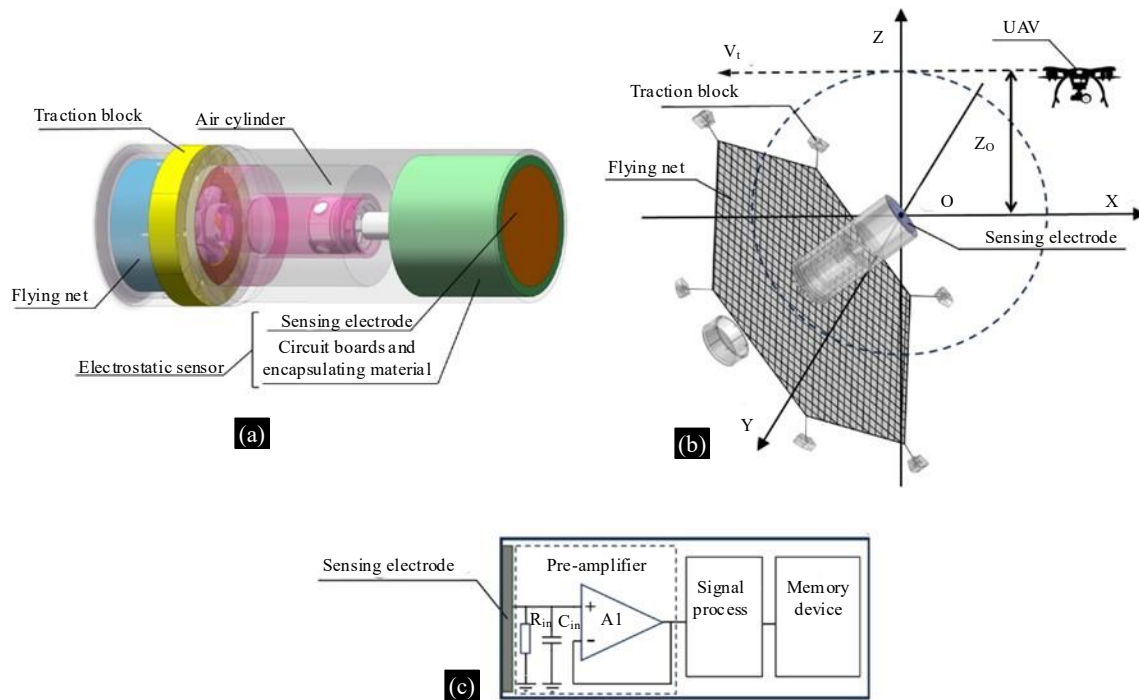


Figure 4. Conceptual diagram of UAV-based air plume sampling.

Challenges include scaling UAV observations to field- or regional-level management decisions and integrating UAV data with agronomic models.

Biodiversity and Wildlife Monitoring

UAVs provide non-invasive ways to survey wildlife populations and habitats. Uses include:

- Counting and mapping colonies (birds, seals) from high-resolution imagery.
- Detecting large mammals using thermal imagery at dawn/dusk to increase contrast.
- Mapping critical habitats (wetlands, coral reefs) and assessing habitat fragmentation.
- Behavioral observation with minimal disturbance when flown at appropriate altitudes and flight profiles (Figure 4).

Ethical considerations: flight altitude and noise, species sensitivity, and regulatory protections for threatened species must guide protocols. Ground-truthing and automated detection algorithms (e.g., CNNs) reduce manual effort [6].

Water Quality, Coastal, and Marine Monitoring

UAV-mounted multispectral and hyperspectral sensors can detect algal blooms, suspended sediment plumes, and surface oil. Radiometric corrections and near-surface sampling for calibration improve quantitative retrievals. UAVs also map coastal erosion, shoreline change, and tidal flat extent using frequent repeat imagery. For bathymetry in shallow, clear waters, UAV-derived photogrammetry (structure-from-motion) can estimate seabed topography using water-penetrating spectral bands, and LiDAR bathymetric sensors (green LiDAR) mounted on aircraft provide more robust results.

Air Quality and Atmospheric Sampling

Small UAVs equipped with gas sensors and particle monitors can sample pollutant concentrations with high spatial resolution around emission sources, urban canyons, and wildfires. Three-dimensional plume mapping captures vertical stratification missed by fixed ground monitors. For greenhouse gas fluxes, combination with meteorological data and plume dispersion models allows emission estimation.

Challenges: sensor response times, contamination, and flow distortion by the platform require careful sensor placement, calibration against reference instruments, and designed flight transects.

Disaster Response and Environmental Hazards

Rapid deployment of UAVs after earthquakes, floods, landslides, and oil spills offers critical situational awareness. Drones quickly collect imagery for damage assessment, search and rescue, and monitoring of hazardous material spread. Thermal sensors aid in finding survivors; multispectral mapping informs hazard extent and recovery planning.

Time-critical operations need robust flight plans, redundancy, and integration with emergency response protocols.

DATA PROCESSING, ANALYTICS, AND INTEGRATION

Photogrammetry and 3D Reconstruction

SFM and multi-view stereo (MVS) pipelines convert overlapping RGB images into dense point clouds, orthomosaics, and DSMs. Accurate georeferencing uses ground control points (GCPs) or RTK/PPK GNSS systems for centimeter-level accuracy. Processing considerations include image overlap (typically 60–80% forward and side overlap), camera calibration, and illumination variability.

Radiometric and Geometric Correction

Multispectral and hyperspectral data require radiometric calibration to convert digital numbers to reflectance using calibration panels and sunlight sensors. Atmospheric corrections may be necessary even at low altitudes under variable illumination. Thermal imagery requires emissivity corrections for accurate temperature retrieval.

Machine Learning and Automated Feature Extraction

Deep learning, particularly convolutional neural networks (CNNs), has been transformative for object detection (animals, tree crowns), semantic segmentation (land cover classification), and change detection. Training requires labeled datasets; transfer learning and data augmentation reduce annotation burdens. Combining spectral, structural, and temporal features improves classification accuracy.

Data Fusion and Scaling

Integrating UAV data with satellite imagery, ground sensors, and models allows scaling from plot to regional inference. Data assimilation frameworks and upscaling algorithms help merge high-resolution UAV snapshots into time-continuous monitoring schemes.

Uncertainty Quantification and Validation

Robust environmental inference requires quantifying uncertainties from sensors, processing pipelines, and models. Cross-validation with independent ground data, reporting of error metrics (RMSE, bias), and open sharing of processing workflows are critical for reproducibility.

LIMITATIONS, CHALLENGES, AND ETHICAL CONSIDERATIONS

Technical and Operational Constraints

- Battery life limits flight duration and coverage, particularly for multirotors; weather (wind, rain) constrains safe operations.
- Payload weight restricts sensor options on small platforms.
- Data storage and processing demands increase with high-resolution and hyperspectral sensors.
- Interference and GPS denial environments present navigational challenges.

Regulatory and Legal Frameworks

Regulations governing UAV operations vary widely by country and region, often limiting beyond-visual-line-of-sight (BVLOS) flights, maximum altitudes, and operations near people or protected areas. Environmental researchers must comply with local aviation authorities, obtain permits, and, where necessary, consult institutional review boards for wildlife disturbance.

Privacy and Societal Concerns

High-resolution imagery can inadvertently capture private property and individuals. Ethical protocols, anonymization, and clear data-use policies are necessary, particularly in populated landscapes. Community engagement and transparency about data use build trust.

Ecological Disturbance and Animal Welfare

Drones can disturb wildlife through noise or perceived predation risk, altering behavior or causing nest abandonment. Best practices include altitude thresholds, approach angles, timing restrictions (avoid breeding season), and pilot training to minimize impacts. Researchers should design studies that weigh knowledge gains versus potential harm and obtain relevant ethical approvals.

Data Management and Reproducibility

Large datasets require robust management plans covering storage, metadata, long-term archiving, and access. Open data principles and sharing of processing scripts enhance reproducibility and accelerate scientific progress.

CASE STUDIES AND EXEMPLAR WORKFLOWS (SHORT SUMMARIES)

Forest Carbon Mapping

Combining UAV LiDAR with multispectral imagery and field allometry yields precise AGB estimates across heterogeneous forests.

Typical workflow: pre-flight calibration

- Concurrent LiDAR and multispectral acquisition
- Point-cloud processing and canopy metric extraction
- Regression modeling with field plots
- Validation and uncertainty assessment (Figure 5).

Urban Air Pollutant Plume Tracing

Small multirotor UAVs carrying calibrated NO_x and PM sensors fly transects perpendicular to a suspected source at multiple altitudes, creating 3D concentration maps interpreted with local wind data to estimate emission rates. Key steps: sensor calibration, tight time synchronization, and paired meteorological measurements.

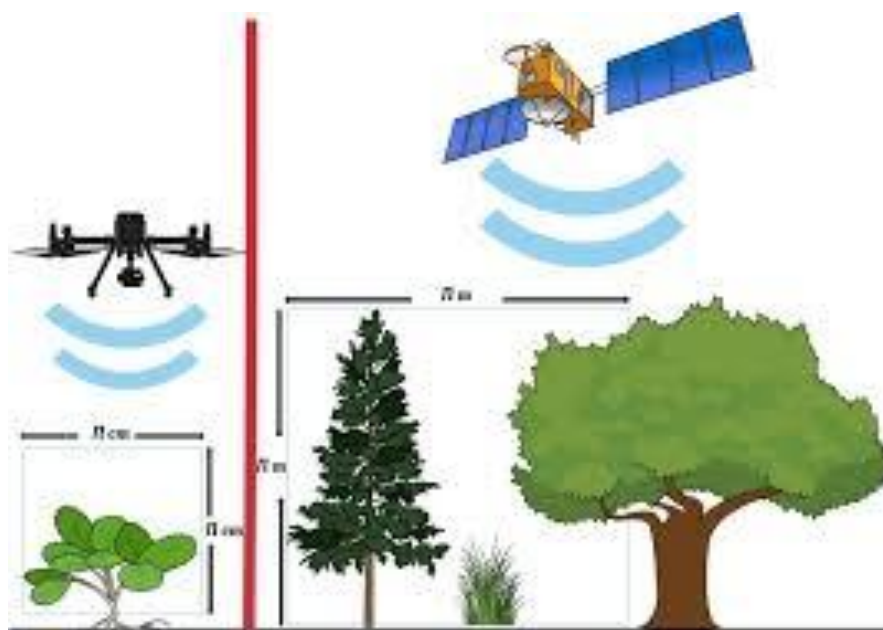


Figure 5. Data fusion across scales.

Coastal Erosion Monitoring

Fixed-wing UAVs conduct repeat flights along shorelines to produce orthomosaics and elevation profiles; differential analyses across temporal baselines quantify erosion/accretion, supporting coastal management decisions.

EMERGING TRENDS AND FUTURE DIRECTIONS

Autonomous and Swarming Systems

Research on coordinated multi-UAV systems (swarms) aims to increase spatial-temporal coverage for tasks like large-scale wildlife surveys and multi-point atmospheric sampling. Advances in decentralized control, collision avoidance, and distributed sensing will enable more resilient monitoring networks.

Miniaturized and Novel Sensors

Continued miniaturization will bring advanced sensors (compact hyperspectral, tunable laser spectrometers) to smaller platforms, expanding capabilities for chemical detection and species-level discrimination.

Edge Computing and Onboard AI

Deploying models onboard UAVs enables real-time detection and decision-making (e.g., adaptive flight to follow detected animals or anomalies), reducing data bandwidth needs and accelerating response times.

Standardization and Interoperability

Community-led protocols for data collection, metadata standards, and open-source processing pipelines will facilitate data integration across studies and regions, improving longitudinal environmental assessments [7-10].

Socio-Ecological Integration

Combining UAV-derived ecological data with social science approaches (community mapping, participatory monitoring) increases relevance for management and promotes equitable use of UAV technologies.

Recommendations and Best Practices

- Design studies with clear objectives linking UAV capabilities to specific ecological questions; avoid data collection as an end in itself.
- Use appropriate platform–sensor combinations; pilot tests help optimize flight parameters (altitude, overlap, time of day).
- Calibrate sensors and include GCPs or RTK/PPK for spatial accuracy.
- Incorporate rigorous validation with field data; report uncertainty metrics.
- Anticipate regulatory and ethical constraints: secure permits, minimize wildlife disturbance, and address privacy concerns proactively.
- Plan for data management: metadata, archival, and sharing mechanisms.

CONCLUSION

Drones have matured into indispensable tools for environmental science, offering unparalleled flexibility in collecting high-resolution spatial and temporal datasets. While technological and regulatory hurdles remain, methodological advances in sensors, analytics, and autonomous systems are accelerating the utility of UAVs across ecosystems and environmental challenges. Responsible, standardized, and ethically guided adoption of UAVs will be central to their continued role in monitoring, conserving, and managing the environment.

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