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Recent Advances in Forest Inventory and Mapping: A Review

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***Abstract*:** Forest inventory and mapping are foundational for effective forest management, enabling systematic assessment of forest structure, composition, biomass, and ecological changes over time. Traditional methods, while historically valuable, are constrained by limited spatial coverage, high labour costs, and slow data processing. Recent technological advances have revolutionized forest inventory practices through the integration of remote sensing platforms, unmanned aerial vehicles (UAVs), robotics, artificial intelligence (AI), and mobile-based data collection tools. Satellite based optical imagery from platforms such as Landsat, Sentinel-2, and Planet Scope facilitates high resolution and long-term monitoring of forest cover and health. Light Detection and Ranging (LiDAR) and Terrestrial Laser Scanning (TLS) enable precise 3D characterization of forest structure and aboveground biomass. Digital Aerial Photogrammetry (DAP), which employs drones to generate point clouds through structure-from-motion algorithms, provides cost-effective alternatives for even-aged forest inventory. Robotic systems such as the FGI ROAMER and Komatsu 931.1 now automate ground-level forest measurements using real-time LiDAR processing, even in GPS-denied environments. Furthermore, AI and machine learning algorithms are increasingly deployed for species classification, biomass estimation, and change detection from satellite and LiDAR data. Mobile-based tools such as Open Foris, Van Darshan, and Forest Watcher enable real-time, geo-tagged forest data collection, improving participatory monitoring and forest governance. Collectively, role and opportunities of these technologies have been over viewed, which offers scalable, accurate, and timely inventory systems essential for sustainable forestry, biodiversity conservation, and climate change mitigation.

***Keywords*:** Forest inventory, Forest mapping, LiDAR, Remote sensing, UAVs, Artificial intelligence

Forest inventory is a systematic process of collecting, analysing, and interpreting data related to forest resources within a defined area. It involves measuring various forest attributes such as tree species, diameter at breast height (DBH), tree height, age, basal area, volume, biomass, and overall forest health. Ferretti et al. (2024) emphasized a well-designed forest inventory creates a comprehensive and scientifically sound database that serves as a baseline for monitoring temporal changes in forest structure and composition. Forest maps may depict forest types, tree cover, canopy density, biomass distribution, and land use changes (Kanga 2017). The various reasons highlighting the importance of conducting forest inventory and mapping are summarized in Table 1. According to Gimrnez-Garcia et al. (2023), forest mapping plays a crucial role in spatial analysis, enabling researchers, planners, and decision-makers to visualize and interpret the spatial heterogeneity of forests more effectively. The inventory provides the raw quantitative data, mapping helps in translating this data into spatial patterns across the landscape (Ferretti et al., 2024). However, conventional forest inventory and mapping methods are often labour-intensive, time-consuming, spatially limited, and prone to human error. In large or inaccessible forest areas, only a small fraction can be surveyed, leading to biased estimates and delayed information (Corona 2010). One of the most significant advancements in recent years is the application of LiDAR (Light Detection and Ranging) technology in forest assessment. LiDAR systems use laser pulses to measure distances to the Earth's surface, enabling the creation of three-dimensional representations of forest structure (Dassot 2011). Modern airborne LiDAR surveys can detect individual trees with a diameter greater than 10 cm with up to 95% accuracy, and can generate canopy height models (CHMs) at resolutions as fine as 1 meter (Zhengnan et al., 2023).

RESULTS AND DISCUSSION

Important conventional techniques of forest inventory and mapping

Strip and plot sampling: Sample plots or linear strips of known dimensions are established systematically or randomly throughout a forest area. Within these plots, tree and vegetation attributes such as Diameter at Breast Height (DBH), tree height, species identity, and regeneration status are recorded. This is one of the most common methods employed by forest departments and research institutions (Kangas and Maltamo 2006, FSI 2021).

Point sampling: This method, also known as angle count sampling or Bitterlich sampling, utilizes tools like angle gauges or prisms to identify trees for measurement based on their apparent width when viewed from a fixed point (Avery and Burkhart 2002, Bitterlich 1984, Gregoire and Valentine 2008).

Timber marking and stock mapping: Trees selected for harvesting are marked with paint or tags, and their positions are noted on paper maps. These maps help document felling series, the distribution of species, and stocking densities. However, these traditional stock maps lack spatial resolution and accuracy compared to modern GPS-based systems (MoEF&CC 2014, Spurr 1952, Chaturvedi and Khanna 2011).

Ocular estimation: Experienced foresters estimate forest parameters such as canopy cover, dominant species, and regeneration status through visual observation. It is often used in preliminary surveys or rapid forest assessments (Somanathan et al., 2009, Husch et al., 2003, Loetsch and Haller 1973).

Quadrat sampling: Fixed-area quadrats (e.g., 1m², 10 m²) are laid out within the forest to systematically record plant species, frequency, density, and coverage. Quadrats can be randomly or systematically placed depending on study objectives (Muller et al., 2018, Misra 1968, Mueller-Dombois and Ellenberg 1974).

Aerial photography: These photos helped identify forest types, canopy gaps, terrain features, and land use patterns. Interpretation was done manually using stereoscopes to view the images in 3D. Though now largely replaced by satellite imagery, aerial photography was foundational in historical forest inventory and mapping (Lillesand and Keifer 2000, Avery 1977, Colwell 1997).

Topographic sheet overlaying: Forest boundaries and compartments were historically traced and mapped over topographic maps issued by the Survey of India. These topographic sheets provided base maps showing elevation, terrain features, and hydrology. Forest boundaries were drawn manually using these sheets, serving as the foundation for early forest maps (FSI 2005, Davis et al., 2001, Burrough and McDonnell 1998).

Compass and chain surveying: A traditional method for boundary demarcation and plot layout, this technique uses a Brunton compass and measuring chains or tapes. It is still used in areas where GPS or digital tools are unavailable (Manandhar et al., 2019, Reddy 1983, Chaturvedi and Khanna 2011).

Plane table and theodolite surveying: Used for terrain mapping, contour creation, and compartment layout, this method provides higher angular precision than compass-based surveys. A plane table is used to record field observations directly onto a map, while the theodolite measures horizontal and vertical angles accurately. It is suitable for detailed surveys of small areas and for producing base maps for forest management (Sharma and Chaudhary 2007, Kiser and Dilger 2008, Husch et al., 2003).

The key limitations and challenges associated with traditional forest inventory and mapping methods are summarized in Table 2**.** To address these challenges, forestry research and practice have increasingly shifted towards modern, technology-driven approaches that are faster, more precise, and scalable. This paradigm shift has given rise to a

Table 1. Need for conducting forest inventories and mapping

Reason	Information	Methodology/Technique used	References
Detection of changes in forest cover	Globally, 420 million hectares of forest area has been lost from 1990 to 2020	Satellite-based remote sensing (multi-temporal Landsat data analysis)	Global Forest Resources Assessment Report, 2020
	Forest and tree cover of India increased by 1445.81 km^2	Remote sensing & GIS mapping (high-resolution satellite imagery by FSI)	Indian State of Forest Report, 2023
Climate change mitigation and carbon stock estimation	289 Giga tons of carbon is being stored by forests worldwide, this information helpful in climate change mitigation efforts like REDD+, NDC's etc.	Global forest inventory & biomass modelling using remote sensing + ground-based plots	Global Forest Resources Assessment Report, 2020
Biodiversity and habitat conservation	Across the globe, forests are home to 80 % of terrestrial biodiversity of which 25 % of them are globally threatened.	Global biodiversity outlook synthesized from ecological monitoring, species inventory databases, and remote sensing	Convention on Biological Diversity, 2020
Forest fire assessment	Around 4 % of forest area is globally affected by wild fires annually	Satellite-based fire detection (MODIS, VIIRS) and GIS-based fire mapping	UNEP Global Wildfire Assessment report, 2022
	Worldwide, 41.82 % of tropical and subtropical forests are highly vulnerable to fires	Remote sensing-based fire risk modelling and spatial vulnerability mapping	
Ecosystem services valuation	Forests contribute 125 trillion dollars per year in ecosystem services like water purification, erosion control *etc*.	Economic valuation models (TEEB framework) integrated with GIS-based ecosystem service mapping	TEEB Report (The Economics of Ecosystems and Biodiversity), 2018
Timber resource assessment for industrial demand	The global timber consumption is projected to reach 5.8 billion cubic meters by 2050, up from 2.2 billion cubic meters in 2018	Statistical modelling and market forecasting using global timber trade datasets	Gresham House Global Timber Outlook Report, 2020

suite of advanced methodologies—ranging from satellite remote sensing and LiDAR to UAVs, robotics, and artificial intelligence—that have transformed the way forests are inventoried and mapped (Wallace et al., 2012, Thaker 2024).

Advancements in forest inventory and mapping: Recent advancements in technologies such as remote sensing, drones, robotics, and AI-based tools are at the forefront of this digital revolution in forestry, reshaping traditional practices and offering new possibilities for forest inventory, health assessment, and restoration (Thaker 2024).

Remote sensing technologies for enhancing forest inventories and mapping: Among the various methods, satellite-based optical imagery, digital aerial photogrammetry, air borne and terrestrial laser scanning plays a pivotal role in detecting forest cover, assessing biomass, monitoring biodiversity, and tracking changes over time (Saukkola et al., 2019, White et al., 2016).

Satellite based optical imagery: Satellite-based optical imagery use sensors aboard satellites to detect and record reflected sunlight across various spectral bands, such as visible, near-infrared, and shortwave infrared (Bayr et al., 2016). Among the most commonly used platforms are medium-resolution satellites like Landsat, which offers a spatial resolution of 30 meters, and Sentinel-2, which provides data at resolutions ranging from 10 to 20 meters (Puliti et al., 2021). Technology has enabled more robust data collection, but operational use of remote sensing (via satellites such as MODIS, Landsat, and Sentinel) for forest phenology monitoring in India is still limited. Remote sensing offers the ability to track large-scale, long-term patterns that are difficult to capture with traditional field methods (Sedha et al., 2024)

For more detailed analysis, high-resolution commercial satellites such as WorldView-3 (0.31 m resolution), Quick Bird, and Geo Eye have proven extremely useful (Alonso et al., 2022, Tokar et al., 2017 and Astola et al., 2010). In real-world applications, the integration of Planet Scope imagery (3 m resolution) with deep learning models has enabled researchers to detect selective logging activities in the Brazilian Amazon, which are often difficult to identify with coarser-resolution datasets (Silva Junior et al., 2021). Such approaches enhance monitoring efforts, especially in areas facing illegal or small-scale deforestation pressures. This has improved the ability to differentiate species at the understory level, which is typically challenging due to dense canopy cover and spectral similarities among vegetation types (Das et al., 2022). Overall, satellite-based optical imagery remains an essential and evolving tool for enhancing forest inventories, offering a cost-effective and scalable solution for long-term forest monitoring and management.

Air borne laser scanning: Airborne Laser Scanning (ALS), commonly known as LiDAR (Light Detection and Ranging), is a cutting-edge active remote sensing technology that enables the capture of the three-dimensional structure of forests with high precision. Unlike passive systems that rely on sunlight, LiDAR operates by emitting laser pulses from an airborne platform (typically an aircraft or drone) and measuring the time it takes for the pulses to return after striking the ground or vegetation. LiDAR is particularly useful in forestry for a range of critical applications (Tonolli et al., 2011). One notable real-world application of this technology is NASA's Global Ecosystem Dynamics Investigation (GEDI), launched in 2019. GEDI uses full waveform LiDAR to measure forest structure and biomass across the globe, providing essential data for global carbon monitoring, climate modelling, and REDD+ (Reducing Emissions from

Table 2. Key factors responsible for the need of advancement

Limitation	Impact	Example	References
Time consuming fieldwork	Slow data collection in large/remote forests	Himalayan ranges require 5–6 weeks per range for inventory	FSI (2021)
Labour intensive	Needs large trained teams & coordination	1000 ha forest may need 8–12 people for 20–25 days	Tripathi et al. (2020)
Limited spatial coverage	Plots cover small % of forest, risking bias	Only 0.1–0.5% area sampled in large forests	Chazdon et al. (2016)
Manual mapping errors	Compass deviations & misplotting common	Hilly terrains show 10–20 m boundary shifts	FSI (2019)
Subjective visual estimations	Observer bias affects canopy cover data	Error margin up to ± 30% between individuals	Nagendra (2001)
No real time monitoring	Fires, encroachments often go unnoticed	Detection can lag weeks/months	Global Forest Watch (2023)
No spatial integration	Hard to overlay with slope, soil, climate layers	Lacks geotagging for GIS compatibility	FAO (2016)
Difficult terrain access	Rugged zones under-surveyed or skipped	Only 30% of steep areas mapped in Nanda Devi Biosphere Reserve	MoEF&CC (2017)

Table 3. Tabular representation of application of drones in forest inventory and mapping

Location	Sensor	Key contribution	Reference
Interior Douglas fir forest	UAV-DAP (ALS)	Detected 246 trees, measured growth between 2013–2015. UAV-DAP estimated avg. tree height growth as 0.68 m and volume growth of 0.05 m^3/tree	Goodbody et al. (2017)
Australia	UAV-LiDAR (ALS)	Measured tree heights with precision comparable to ground-based measurements	Wallace et al. (2014)
Tropical forests of Costa Rica	UAV-DAP (RGB)	Tracked tropical forest recovery, assessed canopy closure and vegetation structure over time	Zahawi et al. (2015)
Coniferous forests of Finland	UAV-Hyperspectral	Detected bark beetle infestation at individual-tree level using spectral traits	Näsi et al. (2015)

Deforestation and Forest Degradation) reporting (Dubayah et al., 2020). In the Indian context, LiDAR has been applied in regions like Karnataka and the Western Ghats to estimate aboveground biomass and model the complex topography of tropical moist deciduous forests. These applications have demonstrated the effectiveness of LiDAR in enhancing forest inventory practices and supporting sustainable forest management strategies (Reddy et al., 2021).

Terrestrial laser scanning: Terrestrial Laser Scanning (TLS) is a ground-based LiDAR technology that uses fixed or mobile scanners to produce high-density 3D point clouds of forest components at tree and plot levels. It is particularly effective for measuring diameter at breast height (DBH), stem taper, branch architecture, and leaf area index (LAI) with high precision. A real-world application of TLS is the TreeQSM algorithm, which reconstructs 3D tree models and accurately estimates aboveground biomass using TLS data (Calders et al., 2015).

Digital aerial photogrammetry: Digital Aerial Photogrammetry (DAP) uses overlapping aerial images captured by drones or aircraft, which are processed through Structure-from-Motion (SfM) algorithms to generate 3D point clouds. In India, drone-based DAP has been employed in the Aravalli Hills and community forests of Maharashtra to assess forest degradation and support joint forest management planning (IIFM Report 2022).

Unmanned aerial systems for precision forest inventory and mapping: Unmanned Aerial Vehicles (UAVs) have emerged as a powerful tool for forest inventory and mapping due to their ability to capture ultra-high-resolution imagery at low altitudes. UAV-based photogrammetry, often referred to as Digital Aerial Photogrammetry (DAP), involves collecting overlapping RGB or multispectral images and converting them into dense 3D point clouds using Structure-from-Motion (SfM) algorithms. Despite certain limitations—such as short flight times due to battery constraints, limited payload capacity for heavier sensors (like LiDAR), and regulatory requirements such as visual line-of-sight rules—UAV-DAP offers a cost-effective, repeatable, and highly adaptable method for forest monitoring. The growing affordability and accessibility of drones, along with advances in image processing software, have further enhanced their utility in generating Enhanced Forest Inventories (EFIs) across diverse forest types (White et al., 2016, Puliti et al., 2020).

AI and mobile based tools: Artificial Intelligence (AI), especially Machine Learning (ML) and Deep Learning (DL) techniques, is playing a transformative role in modern forest monitoring and management. The successful example is use of CNNs with Planet Scope (3 m resolution) and LiDAR data in the Amazon Rainforest, which enabled the detection of selective logging activities with over 90% accuracy (Silva Junior et al., 2021), showcasing the precision and potential of AI-powered monitoring systems. In India, the Forest Survey of India's (FSI) mobile application Van Darshan facilitates photographic inventories of degraded forest patches under the CAMPA scheme. Likewise, the Forest Watcher app from Global Forest Watch (GFW) empowers patrol teams in Congo and Peru by providing offline access to satellite-based deforestation alerts and allowing in-field verification of illegal logging activities. These innovations bridge the gap between remote sensing outputs and field validation, making forest governance more data-driven, participatory, and responsive.

CONCLUSION

Recent advancements in forest inventory and mapping technologies represent a significant paradigm shift from traditional, labour-intensive methods to more efficient, data-driven, and scalable approaches. Today, the integration of advanced tools such as satellite imagery, LiDAR (Light Detection and Ranging), UAV (Unmanned Aerial Vehicle)-based photogrammetry, robotics, artificial intelligence (AI), and mobile data collection platforms has revolutionized the way forest resources are monitored and managed. Collectively, these advancements are not only strengthening local forest governance and sustainable resource management but are also contributing to national and global initiatives aimed at promoting ecological resilience, climate adaptation, and environmental sustainability.

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