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Information and Communication Technology Tools for Geographic Information Systems and Remote Sensing in Forestry: Precision Mapping, Monitoring, and Management

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ABSTRACT: Information and Communication Technology (ICT) tools have transformed Geographic Information Systems (GIS) and Remote Sensing (RS) into indispensable platforms for forestry, enabling high-precision mapping, real-time monitoring, and data-driven decision-making. Key technologies—including cloud-based GIS platforms like Google Earth Engine, LiDAR for structural analysis, and AI-enhanced image processing—facilitate forest inventory, deforestation detection, and carbon stock estimation with accuracies exceeding 90%. These tools integrate drones, GNSS, and multispectral sensors to support sustainable management amid global forest loss rates of 10 million hectares annually. Challenges such as data interoperability, high computational demands, and connectivity gaps persist, yet ICT advancements promise scalable solutions. This review examines core tools, workflows, case studies, impacts, and future directions, highlighting their role in achieving REDD+ and SDG targets through empirical evidence from global applications.

KEYWORDS: ICT, Forest Resource Management, GIS, Remote Sensing (RS), Sustainable Forestry, Geospatial Tools.

I. INTRODUCTION

Forests, spanning 4.06 billion hectares globally, face unprecedented pressures from deforestation, climate change, and biodiversity decline, with 420 million hectares lost since 1990 (FAO, 2024). Traditional forestry relied on manual surveys, prone to errors and inefficiency, but ICT-infused GIS and RS now deliver comprehensive spatial insights. GIS overlays vector data for land-use planning, while RS captures spectral signatures for vegetation health assessment (White et al., 2023).

The evolution traces from 1970s Landsat imagery to modern constellations like Sentinel and CubeSats, augmented by ICT for processing petabyte-scale datasets via cloud computing. In forestry, these tools quantify biomass with RMSE <10%, inform harvest scheduling, and monitor illegal logging (Reiche et al., 2025). National Forest Inventories (NFIs) increasingly adopt them, reducing costs by 50% (Tomppo et al., 2024).

This article details core ICT tools, workflow integration, case studies, impacts, challenges, and prospects, synthesizing meta-analyses to guide forestry practitioners toward precision management.

II. CORE ICT TOOLS AND PLATFORMS

GIS Software and Cloud Platforms

Open-source QGIS and proprietary ArcGIS Pro enable multi-layer analysis, with plugins for forestry metrics like diameter-at-breast-height (DBH) estimation. Cloud platforms like Google Earth Engine (GEE) process

Landsat/Sentinel archives at scale, executing JavaScript APIs for time-series analysis (Gorelick et al., 2023). These ICT tools support collaborative editing via web interfaces.

Remote Sensing Sensors

LiDAR penetrates canopies for 3D point clouds, deriving canopy height models (CHM) with 0.5m vertical accuracy. Synthetic Aperture Radar (SAR) from Sentinel-1 penetrates clouds, ideal for tropical monitoring. Hyperspectral sensors (e.g., PRISMA) distinguish species via 200+ bands, while multispectral Landsat yields NDVI for vigor (Fassnacht et al., 2024).

Data Acquisition ICT

Drones with GNSS/RTK provide cm-level Ortho mosaics, integrated via apps like Forest Mapper. Mobile GIS (e.g., Fulcrum) syncs eld data to cloud servers in real-time, using 4G/5G (Melin et al., 2025).

AI/ML Integration

Convolutional Neural Networks (CNNs) automate classification, achieving 95% accuracy in land-cover mapping. Random forests detect change with <5% omission errors, running on GPU-accelerated platforms like TensorFlow (Reitberger et al., 2023).

These tools form interoperable ecosystems, leveraging APIs for seamless forestry applications.

Integration in Forestry Workflows

ICT workflows fuse RS data via preprocessing pipelines: radiometric correction, co-registration, and fusion (e.g., LiDAR + optical). Standardized NFIs employ wall-to-wall mapping, as in Europe's JRC-Forest service (McRoberts et al., 2024).

Decision Support Systems (DSS) like FORLAND integrate GIS-RS outputs for yield prediction, with Monte Carlo simulations for uncertainty. Blockchain ensures data lineage for carbon credits, while APIs link to ERP systems for supply chains (Pandey et al., 2025).

Dynamic updating via change detection supports adaptive management, reducing inventory cycles from 5-10 years to annual.

Case Studies

India's Forest Survey of India (FSI) uses RISAT SAR and Cartosat DEMs in Bhuvan-GIS, monitoring 2.3% annual deforestation with 92% accuracy, informing compensatory afforestation (FSI, 2024).

Brazil's PRODES/DETER systems process Sentinel/Alerta Amazonas data via cloud ICT, detecting 1.1 million ha deforestation in 2023, triggering real-time alerts (INPE, 2025).

EU's Copernicus High-Resolution Vegetation Layer maps 20 million ha forests biennially using Sentinel-2, with LiDAR validation yielding 89% biomass accuracy (Lang et al., 2024).

US Forest Service's Landscape Change Monitoring uses GEE and aerial LiDAR for 300 million acres, improving carbon estimates by 25% (USFS, 2025).

These demonstrate ICT's global scalability and precision gains.

Technical, Economic, and Policy Impacts

RS-GIS reduces RMSE in volume estimates from 20% to 8%, enabling precise REDD+ accounting (Saatchi et al., 2023). Economically, drone surveys cut costs 70% versus manned flights, with ROI in 2 years (Wulder et al., 2024). Policy impacts include SDG 15 enforcement; ICT dashboards support certifications like PEFC. Capacity building via open platforms democratizes access in developing nations.

Benefits, Challenges, and Comparative Analysis

ICT tools deliver petabyte-scale analysis, sub-meter resolution, and predictive capabilities, revolutionizing forestry precision. Benefits encompass real-time insights and interoperability.

Challenges include cloud costs (\$0.01-0.10/km²), skill gaps, and data silos. Dense canopies challenge optical RS (30% error), while poor broadband limits mobile GIS (Kern et al., 2024).

Table 1: Hybrids optimize most workflows.

Tool/Platform	Forestry Application	Data Resolution/Accuracy	Challenges	Cost/Scalability	Examples
ArcGIS Pro	Inventory, modeling	1m / 95%	Licensing fees, steep curve	Medium/High	USFS inventories
Google Earth Engine	Time-series monitoring	10m / 92%	API limits, compute queues	Low/Very High	PRODES Brazil
Drone-LiDAR	Plot-level CHM	5cm / 98%	Battery, regulations	High/Medium	EU plot sampling
Sentinel-2 Proc.	Wall-to-wall mapping	10m / 90%	Cloud cover, free data lag	Free/High	Copernicus Europe
Mobile GIS	Field validation	cm / 99%	Connectivity, battery	Low/Medium	FSI India surveys

III. CONCLUSION AND FUTURE DIRECTIONS

ICT-enhanced GIS-RS tools are pivotal for sustainable forestry, delivering actionable intelligence amid escalating threats. They underpin resilient ecosystems and economic viability (Mitchard et al., 2025).

Emerging frontiers include 5G for live drone feeds, digital twins for scenario modeling, and CubeSat swarms for daily revisits. Quantum computing may accelerate ML, while federated learning addresses privacy. Policymakers should invest in open data hubs and training, targeting universal NFI integration by 2035.

Holistic ICT adoption promises forests as climate strongholds.

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