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Mapping and Monitoring of Agroforestry Systems by Applying Remote Sensing, GIS, and AI

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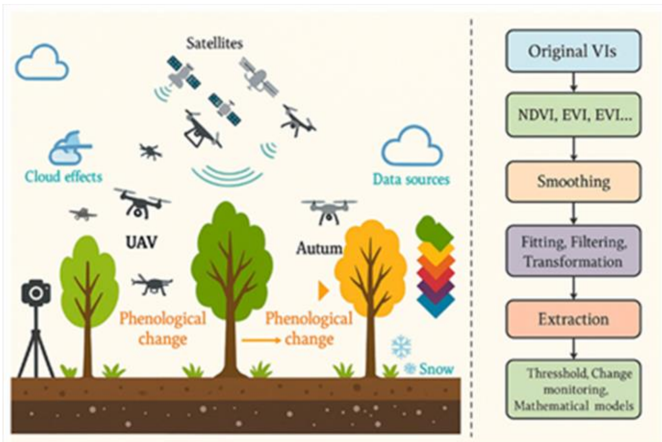
INTRODUCTION

Agroforestry systems, which involve deliberate integration of trees with agricultural crops and sometimes livestock, are increasingly acknowledged as climate-smart land-use strategies capable of enhancing farm productivity while promoting environmental sustainability. These systems contribute to improved soil fertility, enhanced water-use efficiency, biodiversity enrichment, microclimate regulation, and long-term carbon storage. Despite these benefits, detailed characterization and periodic monitoring of agroforestry practices remain difficult due to the complex canopy structures, diverse species composition, and variable spatial distribution. Remote Sensing, GIS, and AI technologies now offer innovative tools that overcome these limitations by providing continuous, multi-scale, and accurate spatial information. By combining satellite data, geospatial models, and intelligent algorithms, researchers, planners, and policymakers can assess agroforestry resources with greater precision and efficiency. This article examines the role of these emerging technologies in mapping and managing agroforestry systems and discusses their future prospects.



(Source, Liang, et al., 2025)

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2. Role of Remote Sensing in Agroforestry Mapping and Monitoring

It provides images of multi-temporal, multi-spectral, and high-resolution features, enabling the detailed observation in agroforestry landscapes: tree cover, canopy structure, vegetation health, and land-use changes.

2.1 Satellite-Based Mapping of Agroforestry

Medium-resolution satellite platforms such as Landsat and Sentinel-2 are widely used to classify land-use and land-cover types, enabling researchers to identify and differentiate agroforestry zones across large landscapes. High-resolution satellite imagery from PlanetScope and WorldView supports the precise detection of individual trees, measurement of canopy density, and analysis of tree–crop spatial arrangements on farms. Synthetic Aperture Radar (SAR) sensors, including Sentinel-1 and ALOS PALSAR, penetrate cloud cover and capture information about vegetation structure, making them extremely valuable for tropical regions where cloud interference is common.

2.2 Vegetation and Tree Health Monitoring

Vegetation indices such as the Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), and Soil Adjusted Vegetation Index (SAVI) are widely used to monitor vegetation vigor, assess crop and tree health, detect nutrient deficiencies, and identify early signs of pest or disease outbreaks. These indices also help in detecting water stress and evaluating drought impacts. Thermal imaging sensors provide additional information on land surface temperature, evapotranspiration rates, and soil moisture patterns, offering insights into microclimate variations within agroforestry systems.

2.3 Estimating Carbon Stocks and Biomass

Remote sensing technologies play a vital role in estimating biomass and carbon stocks. Light Detection and Ranging (LiDAR) provides three-dimensional measurements of canopy structure, enabling accurate quantification of tree height, crown area, and above-ground biomass. Radar backscatter data from SAR sensors assist in assessing woody biomass, especially in dense or mixed vegetation areas. Integrating optical, radar, and LiDAR data enhances the accuracy of carbon accounting models, which are essential for climate mitigation initiatives and carbon credit programs.

3. GIS Applications in Agroforestry Management

GIS is a robust tool for spatial data management, visualization, and analysis that informs planning and management of agroforestry systems at different scales.

3.1 Land-Use and Land-Cover Assessment

The GIS tools map the spatial distribution of agroforestry systems, analyze landscape patterns, assess fragmentation, and evaluate ecological connectivity. The GIS-based LULC maps identify locations where agroforestry expansion or decline in tree cover can be undertaken. Suitability mapping through soil type, elevation, slope, and climatic variables strengthens informed decision-making on site selection.

3.2 Decision Support for Agroforestry Planning

It supports multi-criteria decision analyses to identify the appropriate tree species for a given agro-climatic zone and parts of a landscape where agroforestry interventions could effectively reduce soil erosion and improve land productivity. GIS-based hydrological modeling helps in the estimation of runoff, infiltration, and water harvesting potential, thus allowing for better design of tree-based watershed systems.

3.3 Spatial Monitoring of Environmental Impacts

GIS will allow for the assessment of change in carbon sequestration potential, the valuation of soil and water conservation benefits, and analysis of biodiversity distribution across agroforestry landscapes. Spatial modeling tools help quantify the ecological services provided by agroforestry, supporting policy development and long-term land management strategies.

4. AI and Machine Learning in Agroforestry Mapping

AI and machine learning techniques enhance agroforestry mapping with more detailed accuracy through automated classification and pattern detection, and they create predictive insights.

4.1 Automated Land-Use Classification

Machine learning algorithms such as Random Forest (RF), Support Vector Machine (SVM), and Gradient Boosting offer higher accuracy than traditional classification techniques when identifying agroforestry areas from satellite or drone imagery. Deep learning models, especially Convolutional Neural Networks (CNNs), can automatically detect trees, distinguish between

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agroforestry and natural forests, and identify tree species based on spectral signatures.

4.2 Change Detection and Monitoring

The AI techniques allow for instant detection of changes in land use, which can either show growing or shrinking areas with agroforestry methods. Machine learning algorithms based on time-series data may extract information about vegetation dynamics, seasonality, and long-term tendencies. AI-powered algorithms therefore generate alerts about deforestation, tree loss, and land degradation, among other environmental threats.

4.3 Predictive Modeling to Inform Decision-Making

Machine learning and deep learning models help predict the potential yields of various agroforestry designs, estimate future carbon storage, and assess the suitability of species under projected climate conditions. These predictive tools aid farmers and policymakers in planning climate-resilient interventions in agroforestry.

5. Integrated Utilization of Remote Sensing, GIS, and AI

Integrating remote sensing, GIS, and AI creates a comprehensive agroforestry monitoring and management framework.

5.1 Multi-Source Data Fusion

The combination of optical, radar, thermal, and LiDAR data enhances the accuracy of biomass estimation, the measurement of tree density, and enables detection of understory crops, which are not visually easy in single-sensor imagery. Data fusion techniques also enhance models concerned with carbon accounting and land-use classification.

5.2 Real-Time Monitoring Systems

AI-enabled digital dashboards integrate satellite imagery with GIS layers for real-time monitoring in agroforestry projects. These systems help also in remote advisory services, progress tracking of the plantations, and in the evaluation of projects that helps policy-makers and environmental agencies.

5.3 Support for Climate-Smart Agroforestry

Integrated geospatial tools help in developing climate risk maps, monitoring soil moisture trends, detecting drought conditions, and designing long-term adaptation strategies. This insight helps farmers to select species and develop practices that improve resilience to climate change.

6. Challenges and Limitations

Despite rapid advancements, limitations remain in the mapping and monitoring of agroforestry systems. Closely spaced trees and mixed cropping patterns often create confusion in spectral signatures, making classification difficult. Access to high-resolution satellite data is limited by cost in many developing regions. AI models require quality field data for training, which can be labor-intensive to collect. Technical capacity gaps among extension workers and farmers further constrain widespread adoption of these technologies.

CONCLUSION

Remote sensing, GIS, and AI are increasingly used in the mapping, monitoring, and management of agroforestry systems through providing accurate information related to tree cover, biomass, land-use patterns, and ecological benefits at multiple scales. Integration of geospatial tools with AI-driven analytics offers robust solutions on climate-smart agriculture, carbon accounting, and sustainable land management. The development of low-cost tools, enhancement of technical capacity, access to high-resolution data, and strengthening of institutional frameworks are key areas for future efforts to tap the full potential of these emerging technologies.

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