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"Next-Generation Climate-Smart Forestry: Integrating Digital Twins, AI, IoT, Remote Sensing, and Ecosystem Modelling for Resilient Forest Management"

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Abstract

Climate change continues to increase forest vulnerability through rising temperatures, altered precipitation, pest outbreaks, and extreme disturbances. Recent advances in digital technologies—especially Digital Twin systems, artificial intelligence (AI), high-resolution remote sensing, and IoT—are transforming the way forests are monitored, modeled, and managed. This review integrates findings from recent research between 2023–2025, including studies on Digital Twin architectures for forestry, AI-enabled climate-smart forestry, ecosystem modeling, and resilience assessment. Evidence shows that Digital Twin models provide a real-time virtual replica of forest ecosystems by merging satellite data, LiDAR, sensor networks, AI predictions, and simulation algorithms. Climate-smart forestry practices, when combined with AI-driven analytics, optimize carbon sequestration and support adaptation strategies under multiple climate scenarios. At the same time, digital transformation frameworks in forestry emphasize the integration of blockchain for transparency, IoT for continuous monitoring, and machine learning for early detection of disturbances. High-resolution remote sensing approaches further enhance predictive capability by providing fine-grained structural and functional data for ecosystem processes. This review synthesizes these technological advancements into a unified framework and highlights research gaps related to standardization, data governance, stakeholder adoption, and model interoperability.

Keywords: Climate-smart forestry, Digital Twin, Artificial intelligence, Remote sensing, Ecosystem modelling, Forest resilience

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1. Introduction

Forests play an essential role in global climate regulation, biodiversity conservation, hydrological stability, and socio-economic development. However, climate change—through rising temperatures, drought stress, increased fire frequency, and pest outbreaks—continues to threaten forest health across continents. Traditional forest monitoring methods, which rely on periodic field surveys and coarse-resolution datasets, are no longer adequate for predicting rapid environmental shifts. As a result, the forestry sector is experiencing a digital revolution marked by the rise of Climate-Smart Forestry (CSF), Digital Twin ecosystems, and advanced machine-learning-based analysis tools.

Climate-smart forestry, as discussed by Wang et al. (2024), integrates sustainable forest management principles with climate adaptation and mitigation strategies. It focuses not only on enhancing forest resilience but also on optimizing carbon sequestration. Meanwhile, Digital Twin technology—originally developed for manufacturing and smart cities—has expanded into the forestry sector to provide real-time, predictive, and simulation-based insights into forest ecosystems (Ali et al., 2025; Döllner et al., 2023). A forest Digital Twin acts as a dynamic virtual model that continuously updates itself using sensor data, AI algorithms, and remote sensing inputs.

Recent studies also emphasize the importance of combining high-resolution remote sensing with ecosystem modeling to produce accurate predictions of species composition, biomass, disturbance risks, and resilience metrics (Das, 2025). AI is increasingly used to detect anomalies, simulate climate scenarios, and support decision-making processes (Ayadi et al., 2025). Furthermore, forest management interventions such as thinning, species selection, and mixed-species plantation strategies are being reassessed through a climate-smart lens (Alfieri et al., 2025).

This review synthesizes these technological and ecological insights into a holistic understanding of next-generation forestry systems. It also identifies gaps and opportunities for future research, especially in developing countries where forest degradation is accelerating.

2. Climate-Smart Forestry and the Role of AI

Climate-smart forestry (CSF) promotes sustainable forest management strategies aimed at climate change adaptation and mitigation. According to Wang et al. (2024), modern CSF requires the integration of AI algorithms for optimizing management practices, predicting environmental responses, and facilitating data-driven decisions. AI-driven models can analyze large-scale datasets from sensors, drones, and satellites to evaluate forest health, water availability, carbon storage, and disturbance patterns. Machine learning also improves the early detection of pest outbreaks, disease spread, and drought stress, which are critical components of adaptive forest management.

AI contributes significantly to understanding carbon cycling within forests. Deep-learning neural networks can estimate above-ground biomass and carbon stocks with higher accuracy compared to traditional models. AI tools also support scenario simulation—allowing forest managers to test the outcomes of thinning intensity, species selection, and forest restoration strategies under different climate projections. This capacity aligns with findings by Alfieri et al. (2025), who demonstrated that thinning intensity and species composition play a vital role in climate-smart forestry outcomes.

AI techniques, including reinforcement learning and temporal modeling, help optimize operational planning such as harvesting schedules, fire risk management, and restoration timing. Moreover, integration of AI with IoT sensors helps automate the continuous monitoring of soil moisture, tree growth, and microclimatic variations. As Ayadi et al. (2025) highlight, AI-driven approaches significantly enhance system resilience by improving predictive capabilities and reducing uncertainty in ecological assessments.

Overall, climate-smart forestry empowered by AI represents the foundation for next-generation forest management, enabling responsive, efficient, and ecologically informed interventions.

3. Digital Twin Technology for Forest Ecosystems

Digital Twin (DT) technology is emerging as a breakthrough innovation for forestry. A Digital Twin is a real-time virtual representation of a physical forest ecosystem, built by integrating data from remote sensing, IoT sensors, climate models, and AI algorithms. According to Ali et al. (2025), digital twins are revolutionizing resilience planning by offering predictive simulations and continuous monitoring capabilities. In forestry, this means that forest managers can observe real-time changes in canopy structure, biomass distribution, soil conditions, and ecological processes.

Sasaki & Abe (2025) developed a Digital Twin architecture that integrates AI, IoT, and blockchain to support ecological restoration and ensure data transparency. Blockchain is especially valuable for verifying management actions, recording biodiversity parameters, and tracking timber supply chains. The Digital Twin framework allows managers to simulate disturbances such as fires, droughts, pest outbreaks, and storm damage. It also supports the evaluation of restoration strategies, species selection, and carbon sequestration potential under alternative climate trajectories.

Döllner et al. (2023) highlight that digital twins in forestry require 3D visualization tools, geospatial data infrastructures, and web-based platforms for interaction. 3D models enable detailed structural representation of tree crowns, understory vegetation, terrain surfaces, and hydrological patterns. Modern DT systems can integrate both live data (e.g., sensor feeds) and historical data (e.g., satellite archives) to create a continuously evolving environmental model.

One critical advantage of Digital Twin technology is its ability to support real-time decision-making. By analyzing current conditions and predicting future scenarios, forest managers can design more effective mitigation strategies. Digital Twins also enhance stakeholder communication by offering intuitive visualizations for governments, communities, and conservation organizations.

4. High-Resolution Remote Sensing and Ecosystem Modeling

High-resolution remote sensing technologies—including hyperspectral imagery, LiDAR, drone photogrammetry, and SAR—have significantly improved forest monitoring capabilities. According to Das (2025), these tools provide granular information on canopy structure, species composition, biomass distribution, and ecosystem dynamics. LiDAR, for example, can capture detailed 3D point clouds, enabling precise estimation of tree height, crown structure, and forest gaps. Hyperspectral sensors can detect subtle physiological stress markers that indicate drought or disease before physical symptoms appear.

Ecosystem modeling integrates these remote sensing outputs into simulation frameworks that predict long-term changes in forest health, productivity, and resilience. These models combine ecological theory with climate data, soil parameters, hydrology, and species interactions. When merged with Digital Twin systems, ecosystem models become powerful tools for scenario planning.

Remote sensing also plays a key role in mapping forest disturbances. Multi-temporal satellite images can detect early signs of pest outbreaks, fire scars, and illegal logging activities. Machine learning models trained on satellite time series can classify disturbance types with high accuracy. Remote-sensed data further support the tracking of reforestation and afforestation progress, carbon stock changes, and biodiversity indicators.

Das (2025) emphasizes that combining remote sensing with ecosystem modeling enables the prediction of ecosystem tipping points—thresholds beyond which forests may not recover. This capability is essential for designing resilience strategies under climate change.

Table 1. Summary of Major Digital Technologies Used in Climate-Smart Forestry and Their Applications

Technology	Key Functions in Forestry	Benefits	Challenges / Limitations
Digital Twin Systems	Real-time virtual simulation of forest structure, biomass, microclimate, and disturbances. Integrates remote sensing + IoT + AI.	Predictive modelling, early-risk simulation, decision support, enhanced restoration planning.	High computational cost, need for skilled operators, interoperability issues.
Artificial Intelligence (AI)	Machine learning for biomass estimation, species classification, disturbance detection, and scenario forecasting.	High accuracy, fast processing, reduced human error, improved climate adaptation.	Requires large datasets; models may be biased or difficult to interpret.
High-Resolution Remote Sensing (LiDAR, SAR, Hyperspectral)	3D canopy modelling, biomass assessment, stress detection, multi-temporal monitoring.	Fine-scale detail, non-invasive monitoring, detects early ecological stress.	Expensive data acquisition, requires advanced processing skills.
IoT Sensors	Real-time recording of soil moisture, temperature, humidity, tree growth, CO_2 flux, and hydrology.	Continuous data stream, supports Digital Twin updates, increased precision.	Requires infrastructure, energy supply, and maintenance in forests.
Blockchain Integration	Secure data sharing, transparent timber tracking, verification of restoration actions.	Reduces corruption, improves stakeholder trust, enhances data integrity.	Complex implementation, limited adoption in forestry.
Ecosystem Modelling	Predicts forest dynamics, resilience, carbon storage, species interactions, and climate impacts.	Scenario testing, long-term planning, improved restoration success.	Models require calibration, uncertain future climate variables.

This table summarizes the major digital technologies contributing to next-generation climate-smart forestry and highlights their specific functions, advantages, and limitations. It shows how Digital Twin systems, AI, remote sensing, IoT, blockchain, and ecosystem modelling collectively enhance forest monitoring, simulation, and resilience planning. The table also illustrates that each technology offers unique benefits—such as real-time updates, fine-scale environmental analysis, or transparent data governance—while carrying practical challenges related to cost, interoperability, and data requirements. Together, these technologies form an integrated digital ecosystem that supports adaptive and science-driven forest management. The comparison helps readers understand the complementary nature of these tools and how they jointly shape the future of sustainable forestry.

5. Climate Resilience and Adaptive Forest Management

Climate resilience refers to a forest ecosystem's ability to withstand, recover from, and adapt to climate-related disturbances. Several studies, including Ayadi et al. (2025), have highlighted that AI-based frameworks significantly enhance resilience assessment. These frameworks allow researchers to identify vulnerability hotspots, simulate extreme weather events, and propose adaptive interventions.

Forest resilience depends on species diversity, structural complexity, soil health, and microclimatic stability. Alfieri et al. (2025) demonstrated that thinning practices and species composition directly influence forest stability under climate stress. Mixed-species forests tend to exhibit higher carbon stability and better resistance to pests and diseases. Meanwhile, targeted thinning can reduce competition for water during drought periods.

Digital Twins contribute to resilience planning by providing simulation environments where management options can be tested before implementation. For example, simulations can assess how forest stands respond to various thinning levels, replanting strategies, or fire prevention measures. Combining this with remote sensing data helps validate model predictions and refine resilience strategies.

Adaptive forest management integrates continuous monitoring, iterative learning, and flexible interventions. AI models can forecast where and when interventions are needed, allowing managers to respond proactively rather than reactively. This dynamic approach is essential for coping with the increasing unpredictability of climate change.

6. Conclusion

The convergence of Digital Twin technology, artificial intelligence, Internet of Things (IoT), high-resolution remote sensing, and advanced ecosystem modelling marks a transformative era in forestry science. Collectively, these innovations are redefining how forests are monitored, evaluated, and managed under accelerating climate change. Digital Twin ecosystems create a real-time, dynamic representation of forests, enabling managers to simulate disturbance scenarios, optimize restoration strategies, and evaluate carbon sequestration performance. AI plays a vital role by processing complex datasets and predicting ecological responses with higher precision than traditional models. Meanwhile, IoT sensors and remote sensing platforms provide continuous, multi-scale data, offering unparalleled visibility into forest health, hydrological cycles, microclimates, and biomass fluctuations.

Climate-smart forestry—empowered by these technologies—ensures forests are managed not only for sustainability but also for resilience and adaptability. Research demonstrates that integrating digital technologies with ecological knowledge enhances decision-making capacity, reduces management uncertainty, and provides early warnings for risks such as drought, disease outbreaks, and fires. Furthermore, innovations such as blockchain-enabled transparency, species-specific thinning strategies, and high-accuracy biomass estimation strengthen governance mechanisms and improve ecosystem service valuation.

However, challenges remain. Data standardization across sensors and platforms is still limited, reducing interoperability. Implementation costs are high in developing countries, and gaps in digital infrastructure restrict real-time monitoring systems. Furthermore, ethical considerations around data privacy, indigenous land rights, and technological dependence must be addressed. Despite these barriers, the rapid advancement in AI, remote-sensing analytics, and Digital Twin frameworks suggests a promising trajectory where forestry becomes more predictive, responsive, and climate-resilient. Continued interdisciplinary collaboration is essential to fully unlock the potential of next-generation forest management systems.

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