Annals of Silvicultural Research
50(2), 2025: 32-35
https://journals-crea.4science.it/index.php/asr

Concept note

Integrating artificial intelligence to support systemic advances in silviculture

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Received: 23/07/2025 Accepted: 23/08/2025 Available online: 3/11/2025

ABSTRACT Silviculture is playing an increasingly vital role in addressing global environmental challenges such as climate change, biodiversity loss and the rising demand for forest resources. In this context, the integration of artificial intelligence (AI) into forestry practices has recently emerged as a promising pathway. The potential benefits are substantial: AI offers the promise of greater operational efficiency and more informed, data-driven decision-making. However, the transformative potential of AI extends well beyond the mere automation of existing processes. It may contribute to a shift in the conventional management paradigm: from decision-making based on static, periodically updated plans to an approach where decisions are continuously informed and refined by real-time data streams and model outputs. This evolution supports the emergence of truly adaptive silviculture, aligned with the principles of complex adaptive systems. On the other hand, the effective integration of AI into silviculture also presents notable limitations and research challenges. Key issues include the need for robust AI models tailored to the intricacies of dynamic forest ecosystems, the development of cost-effective methods for data acquisition and management, the advancement of explainable AI for greater transparency and trust and the careful consideration of the ethical, social and economic implications associated with AI adoption in forest management. This note explores these subjects through a commented discussion.

KEYWORDS: Forest management, complex adaptive systems, machine learning, deep learning, reinforcement learning, computer vision, natural language processing, decision support systems.

Possible confluence of AI and silviculture

Contemporary silviculture faces mounting pressures, including the urgent need to meet growing societal demands for both timber and non-timber forest products, conserve biodiversity and implement effective climate change mitigation and adaptation strategies (Corona and Alivernini 2024). These challenges are compounded by the fact that silvicultural practices are often labor-intensive, costly and may lack scalability, especially when confronted with today's complex, large-scale and interconnected socioecological dynamics.

The integration of artificial intelligence (AI) has recently emerged as a promising pathway for enhancing forest management (e.g., Malo et al. 2021, Nitoslawski et al. 2021, Buchelt et al. 2024, Hyo-Vin et al. 2024, Wang et al. 2025). This convergence is not merely a technological trend, but rather a potential turning point for the discipline, leveraging AI's capacity to manage the complexity and scale inherent to forest ecosystems.

Within the broader context of forest management, this concept note specifically explores key issues and emerging trends in the application of AI to silviculture. It highlights the transformative potential of AI tools and methods, while also addressing the critical limitations that hinder their practical implementation. Furthermore, it outlines research priorities for guiding responsible and effective advancement in this domain.

AI-driven methods and tools in silviculture

The application of AI in forest management spans a broad range of techniques and methods, as shown in Table 1. Key issues specific to silviculture include:

(i) growth and yield modeling: AI techniques, particularly machine learning (ML) and deep learning (DL), may enhance conventional approaches used to assess forest dynamics, growth rates and timber yields, offering increased robustness under changing environmental and climatic conditions (Boukhris et al. 2025);

(ii) proactive risk management: AI facilitates a shift from reactive to proactive interventions by integrating heterogeneous data sources to assess the spread and impact of wildfires, windstorms and other disturbances (Ali et al. 2025);

(iii) decision support systems (DSS): AI-powered decision support systems can enhance the comprehensiveness and robustness of silvicultural intervention planning (Yadav et al. 2024).

The evolution of AI methodologies is tightly coupled with advancements in data acquisition technologies. For instance, the shift from ML to more sophisticated DL approaches has been enabled by the growing availability of high-resolution, multimodal data from satellites, LiDAR and unmanned aerial vehicles. This co-evolutionary dynamic, where richer data enables more powerful AI approaches which in turn drive demand for finer data, accelerates the operational potential of AI.

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http://dx.doi.org/10.12899/asr-2681

Table 1 - Examples of applications of AI methods and tools in forest management.

AI method / tool	Brief description	Specific applications	Selected enabling data / technology
Machine learning (e.g., RF, SVM, ANN)	Algorithms that learn from data to make assessments or decisions	Species identification, pest/disease assessment, yield modeling, site classification, risk assessment	Historical records, field survey data, sensor data, remotely sensed imagery
Deep learning (e.g., CNN, RNN, LSTM)	ML using multi-layered neural networks for hierarchical feature learning from large datasets	Image-based tree species identification, disease/pest symptom detection, deforestation mapping, biomass estimation from imagery, forest fire prediction, analysis of 3D point clouds	High-resolution imagery (satellite, UAV), LiDAR point clouds, extensive sensor datasets
Computer vision	Enables machines to interpret and understand visual information from images/videos; often uses DL	Tree species identification (leaf, bark, canopy), forest inventory (tree counting, density), health monitoring (discoloration), deforestation detection, biomass estimation from visual data	Drone/satellite/aerial imagery, ground-level photos/videos
Reinforcement learning (e.g., Q-learning)	Agents learn optimal actions through trial-and-error interaction with an environment to maximize rewards	Adaptive forest management srategies, sustainable harvest planning, balancing multiple objectives (economic/ecological) under uncertainty, wildfire response strategies	Simulation environments, dynamic forest models, GIS data, economic/ecological parameters
Natural language processing (e.g., LLMs)	Enables computers to process, understand, and generate human language	Analysis of scientific literature & policy documents, knowledge extraction for forestry databases, information dissemination	Textual data (research papers, reports, policies, field notes)
Expert systems / Decision support systems	Systems emulating human expert decision-making; often AI-enhanced	Tree selection for planting, management intervention planning, climate resilience assessment, balancing ecosystem utilities, sustainable harvesting advice	Integrated datasets (climate, soil, species traits, economic data), AI/ML model outputs

Transformative potential of AI in silviculture

It is somewhat surprising that the transformative potential of AI in silviculture has not yet been fully recognized, at least in the scientific literature. Its potential extends well beyond task automation and offers a foundation for a fundamental shift toward holistic, adaptive ecosystem management. One notable example is the development of digital forest twins (dynamic virtual replicas of forest stands and landscapes) which enable advanced simulations of ecosystem processes, disturbance responses, and silvicultural interventions.

In principle, with AI, silvicultural decisions need no longer rely on static, periodically updated plans. Instead, they could be continuously informed and adapted based on real-time data streams and AI-enhanced DSS. This integration effectively dissolves the traditional separation between planning, implementation and monitoring, replacing it with a dynamic feedback loop in which forest conditions and silvicultural strategies evolve together.

Such a shift closely aligns with the theory of complex adaptive systems, departing from rigid management cycles in favor of truly adaptive silviculture and allowing for flexible, responsive and context-specific interventions that are better suited to the complexities of forest systems (Messier et al., 2013, Nocentini et al. 2017, 2021).

Navigating the frontiers: limitations and research challenges

Despite its potential, the integration of AI into forest management faces several critical challenges, as outlined in Table 2. The underlying issues driving these challenges, particularly in the context of silviculture, include:

(i) data dependency and quality: AI models, particularly DL architectures, rely heavily on large volumes of high-quality, accurately labeled training data; collecting such data in remote and heterogeneous forest environments is often costly and logistically demanding; inconsistent or noisy data can severely impair assessment performance and generalizability; furthermore, the lack of standardized, open-access benchmark datasets for silvicultural applications may hamper comparative evaluation and scalability;

(ii) model opacity (the “black box” problem): many advanced AI models operate as opaque systems, making it difficult to interpret their decision-making processes; this reduces trust among forest managers and stakeholders who require transparency and justifiability, especially for compliance and accountability; the development of explainable AI (XAI) methods tailored to forestry is therefore a research priority;

(iii) computational demands: training and deploying AI models at scale requires high-performance computing resources, including central and graphic processing units and large data storage systems; the associated costs can be prohibitive for smaller organizations and professionals, potentially creating disparities in access and benefit;

(iv) human resources: alongside hardware and software, effective AI implementation require skilled personnel for tool usage and data interpretation, as well as substantial upfront investment in training; without targeted efforts, such as open-source solutions, accessible platforms and global capacity-building initiatives, the high demands for both computing power and human expertise risk deepening the existing divide between well-resourced and under-resourced organizations and regions;

(v) integration with existing knowledge and practices: AI-generated recommendations may conflict with traditional knowledge or established management routines, complicating adoption; therefore, successful integration depends on ensuring that AI augments, rather than replaces, human expertise and that it aligns with real-world decision-making and monitoring frameworks.

Many of these challenges are interlinked. For instance, model opacity limits trust, which discourages data sharing and collaboration, ultimately stalling AI development. Breaking this cycle requires transparency, inclusive stakeholder engagement, and clear communication about AI's capabilities and limitations: participatory approaches may offer valuable frameworks for addressing these issues (Chisika and Yeom 2024).

Concluding remark

The most recent World Congress of the International Union of Forest Research Organization has emphasized the need to "… transform forest-related sciences for the future through responsible use of innovative and emerging technologies, digitalization, and artificial intelligence supported tools in the forest sector based on a fuller understanding of their socio-economic and ethical implications" (IUFRO 2024).

Table 2 - Selected overview of the potential, limitations and research frontiers of AI in forestry.

Issues	AI-driven potential	Current limitations	Research challenges / future directions
Forest inventory & mapping	Automated species ID, accurate biomass/carbon stock estimation, rapid large-scale inventory	Data requirements (volume, quality), cost of high-res sensors (LiDAR, HSI), model generalizability across diverse forests	Develop cost-effective sensors, standardized open datasets, improved algorithms for heterogeneous forests, synthetic data generation
Forest health monitoring	Early pest/disease detection, stress monitoring, tracking restoration success, real-time alerts	Distinguishing stress factors, model accuracy in complex canopies, data processing for real-time alerts	Enhance multi-sensor data fusion, develop robust models for subtle symptom detection, XAI for diagnostics, lightweight models for edge deployment
Growth, yield & harvesting	Improved yield forecasting, harvest schedules balancing economic/ecological goals, efficient resource allocation	Complexity of growth models, integrating market dynamics & ecological constraints, uncertainty in predictions	Advance RL for multi-objective optimization, integrate climate change scenarios into yield models, develop adaptive management algorithms
Risk management (fire, windstorm, etc.)	Predictive fire assessment, predictive windstorm assessment, drought assessment, early illegal logging detection	Accuracy of long-range predictions, false alarm rates, integrating dynamic environmental data	Improve predictive accuracy with real-time data streams, develop AI for rapid response coordination, enhance models for cascading risks
Data & AI models	Handling vast datasets, complex pattern recognition, automation of repetitive analytical tasks	Data scarcity/quality issues, "black box" models, high computational costs, model validation difficulties	Create robust data pipelines, advance XAI techniques, develop efficient training methods (e.g., transfer/few-shot learning), establish model validation protocols
Implementation & ethics	Enhanced decision-making, increased efficiency, potential for wider community participation	High initial costs, lack of skilled personnel, cultural resistance, ethical concerns (bias, privacy, job displacement), policy gaps	Develop ethical AI frameworks for network resource management, promote capacity building & training, ensure equitable access, foster participatory AI design, create supportive policies

The desired trajectory of AI in silviculture suggests a paradigm shift toward a discipline that is increasingly data-driven, adaptive and equipped to tackle complex socio-ecological challenges (Corona et al. 2025). However, realizing this potential depends on addressing the limitations outlined above. Bridging the gap between AI developers, computer scientists, forest professionals and managers is essential to ensure that AI applications in silviculture are ecologically grounded, socially accepted and practically implementable.

Ultimately, advancing this field requires more than just technical innovation: it demands a comprehensive socio-technical systems approach that integrates algorithm and infrastructure development, supportive training and policy frameworks, inclusive stakeholder engagement, and equitable access to the benefits of AI.

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