Towards Intelligent Forestry: Big Data, Machine Learning, and Sustainable Management Strategies

Romeet Saha

ABSTRACT

Data-driven, precision forest management exemplifies a shift from traditional practices to big-data analytics, which leverages advanced computational technologies while addressing complex environmental challenges. Research has shown how big data analytics has become an important enabler for sustainable forest management and provides unprecedented opportunities for monitoring, analysis, and decision-making at every step. Remote sensing technology, Internet of Things (IoT) sensors, machine learning algorithms, cloud computing platforms, and block chain systems are some of the key technologies being deployed in this market. Results indicate an increase of the accuracy of forest classification applications to 85-98% with significant improvement in operation efficiency and cost reduction. However, the data integration problems, system interoperability, technical ability, and economic accessibility still exist.

Romeet Saha[1]

[1]Assistant Professor
Department of Forestry, Royal Global University, Guwahati 781035, Assam, India

Email: saharomeet@gmail.com

This review provides a comprehensive framework for the transformation potential that big data analytics can add to the solution of contemporary challenges in forestry, including minimizing climate change adaptation, biodiversity conservation, sustainable resource utilization, and supply chain transparency.

Keywords Big data analytics, Smart forestry, Machine learning, Remote sensing, IoT, Blockchain, Precision forestry, Forest management.

INTRODUCTION

Forests are one of the most important ecosystems because of their role in the provision of various vital services such as carbon sequestration, biodiversity, water management, and timber (Jing *et al.* 2023). Nevertheless, forests are challenged there like never before due to the impact of climate change, deforestation, illegal logging, pest outbreaks, and the growing needs of housing and forest products and services (Estrada *et al.* 2023). The conventional forest management approaches of the manual data collection with limited spatial information and reactive decisions are rather inadequate to handle these compound and interconnected challenges (Fassnacht *et al.* 2024).

The advent of big data analytics in forestry is an opportunity for revolutionizing the means of forest management through the fusion of cutting-edge remote-sensing technologies, machine learning

algorithms, and cloud computing platforms (Zou *et al*. 2019). Big data analytics in forestry is a process of collecting, processing, and analyzing massive amounts of data from multiple sources, including satellite imagery, lidar systems, Internet of Things (IoT) sensors, unmanned aerial vehicles (UAVs), and ground-based monitoring networks, among many others (Ayankoso *et al*. 2024).

This collusion of technologies means that foresters and researchers get unprecedented levels of understanding about forest dynamics, help optimize management decisions, and carry out precision forestry practices to improve not just economic but also ecological outcomes (Rossit *et al*. 2019). The framework for the forestry big data proposed by Zou *et al.* (2019) comprised five layers. The data acquisition layer, the data storage layer, the data processing layer, the data analysis layer, and the application layer had

a complete data framework for understanding and implementation of a big data solution for forestry.

Big data technologies in forestry applications

Overview of technologies

The application of big data analytics in forestry involves multiple interconnected technologies, each contributing unique capabilities for forest monitoring, analysis, and management. Table 1 summarizes the key technologies, their applications, and performance characteristics.

Remote sensing technologies

Satellite remote sensing is currently one of the key technologies in the monitoring of forests at a large scale and provides stable and repeatable observations

Table 1. Big data technologies in forestry applications (Fassnacht *et al*. 2024, Jing *et al.* 2023, Zou *et al*. 2019).

Technology	Primary applications	Data volume handled	Accuracy rate (%)	Cost effectiveness	Implementation complexity
Remote Sensing (Satellite)	Forest cover mapping, deforestation monitoring, biomass estimation	Petabytes/year	85-95	Medium	Medium
LiDAR	Canopy height measurement, 3D forests structure analysis	Terabytes/day	90-98	High	High
IoT Sensors	Real-time environmental monitoring, fire detection	Gigabytes/day	80-90	Low	Low
Unmanned Aerial Vehicles (UAVs)	High-resolution imagery, forest health assessment	Terabytes/week	88-96	Medium	Medium
Machine Learning	Species classification, predictive modeling	Terabytes/month	85-94	High	High
Deep Learning	Pattern recognition, automated forest inventory	Petabytes/month	88-98	High	Very High
Cloud Computing	Data storage, processing, scalable analytics	Exabytes/year	90-99	High	Medium
Block chain	Supply chain traceability, carbon credit verification	Gigabytes/day	95-99	Medium	High
Geographic Information Systems (GIS)	Spatial analysis, forest management planning	Terabytes/month	85-92	Medium	Medium
Artificial Intelligence	Automated decision making, intelligent monitoring	Terabytes/day	87-95	High	Very High
Edge Computing	Real-time processing, distributed analytics	Gigabytes/hour	82-91	Medium	Medium
Big Data Analytics Platforms	Large-scale data processing, pattern mining	Petabytes/month	86-93	High	High

in large geographic scales (Fassnacht *et al*. 2024). The latest satellite technologies (e.g., Landsat, Sentinel-2, and commercial high-resolution platforms) deliver petabytes of data annually, which can be used to map forest cover, deforestation, and biomass estimation throughout the world (Zhang *et al.* 2020). Hyperspectral and multispectral imagery with machine learning algorithms has significantly increased the accuracy of forest attribute estimation, and research has indicated classification accuracy of more than 90% with applications of forest cover mapping.

Recent advances in satellite-based forest monitoring include automated change detection algorithms capable of detecting cases of deforestation days after it happens. It has been observed that time-series analysis of satellite-derived data is one of the most valuable methods to track forest dynamics, and research demonstrated that it was possible to observe small trends in the health of the forest, its growth peculiarities, and disturbances. Integration of different satellite sensors and plotted time series data has made it possible to develop strong forest monitoring systems that can provide near-real-time information on the condition of forests (Arab 2022).

A new technology - The light detecting and ranging (LiDAR) technology that is used to analyse the structural components of forests, giving detailed information of the canopy of the forest, and its vertical structure. With aircraft LiDAR systems, it is possible to generate point clouds that have millions of measurements per hectare to be utilized to estimate tree height, crown size, and canopy cover along with aboveground biomass with great precision. LiDAR, combined with machine learning, has already been shown to be an extraordinarily precise forest inventory tool with biomass estimation errors down to 15% in multiple forest types.

Sensor networks and internet of things

Internet of Things (IoT) have changed the way forests are monitored to offer real-time constant data of sensor networks that are distributed throughout the forests (Ayankoso *et al.* 2024, Singh *et al.* 2022). IoT technology can be applied in the forest ecosystem to monitor temperature, humidity, soil moisture, air quality, and other desirable environmental variables at a high spatial and temporal resolution. These sensor networks produce enormous volumes of data, which provide us information on the dynamics of the forest ecosystem and early identification of environmental threats before they develop.

There are also challenges associated with wireless sensor networks that are used in forests, like power consumption, range of communication, and robustness in the environment. The recent advances in low-power wide-area network (LPWAN) technologies, energy scavenging systems, and strong sensor design have helped to address most of these issues, and the IoT systems can be deployed in remote forest areas on a long-term basis. The IoT-based systems of monitoring have proven effective in their application in the fire detection systems, tracking of wildlife, and monitoring of microclimate, among others.

IoT-based fire detection systems are one of the most effective applications of big data analytics in the forestry industry, and they can provide an early warning of fire incidents and respond to the threat efficiently and dramatically. There are a number of sensors that are integrated into fire risk assessment systems, such as smoke detectors, temperature sensors, humidity sensors, and gas analysis sensors. The streams of sensor data are analyzed using machine learning algorithms to find fire signatures and distinguish a true fire event from a false alarm (Gao *et al.* 2022).

Machine learning and artificial intelligence applications

Machine learning algorithms in forestry

The application of machine learning algorithms in forestry has demonstrated significant potential for automating complex analytical tasks and improving decision-making processes. Table 2 summarizes the key machine learning algorithms used in forestry applications.

Deep learning for forest analysis

Deep learning algorithms have been shown to be

Table 2. Machine learning algorithms in forestry big data analytics (Yun *et al.* 2024, Estrada *et al.* 2023, Zou *et al.* 2019).

Algorithm	Primary use case	Accuracy range (%)	Data requirements	Computational complexity	Interpretability
Random Forest	Species classification, Biomass estimation	88-96	Medium-Large	Medium	Medium
Support Vector Machine	Pattern recognition, Classification	85-93	Small-Medium	Medium	Low
Convolutional Neural Networks	Image analysis, Object detection	90-98	Large-Very Large	Very High	Very Low
XGBoost	Predictive modeling, Feature selection	87-95	Medium-Large	Medium-High	Medium
Long short-Term Memory	Time series forecasting, Sequence modeling	82-91	Large	High	Low
Decision trees	Decision support, eule extraction	80-88	Small-Medium	Low	High
K-Means Clustering	Data clustering, pattern discovery	75-85	Medium	Low-Medium	Medium
Linear Regression	Growth modeling, Trend analysis	78-86	Small-Medium	Low	High
Naive Bayes	Probabilistic classification	79-87	Small-Medium	Low	High
Ensemble Methods	Model combination, Accuracy improvement	89-97	Large	High	Low-Medium

excellent tools for forest analysis applications, as they can automatically learn complex patterns from high-dimensional data (Yun *et al.* 2024). Convolutional Neural Networks (CNNs) have been found to be particularly useful for working with satellite imagery and aerial photography and have produced state-of-the-art results for the classification of forest cover, species identification, and change detection. Recent work has reported accuracies in excess of 95% for classification for forest type mapping using deep learning techniques.

Application of deep learning to LiDAR point cloud analysis has opened up possibilities of advanced three-dimensional forest analysis via individual tree segmentation, canopy structure characterization, and biomass estimation. Recently, deep learning-based methods like PointNet and 3D-CNN were designed to learn from three-dimensional forest data and obtain impressive accuracy even in complex forest environments. Transfer learning techniques have further increased the applicability of deep learning models to different forest types and geographic regions (Shokri *et al.* 2023).

Predictive modeling and decision making

Machine learning algorithms can help to accomplish complex predictive modelling in forest management applications for evidence-based decision-making over multiple temporal and spatial scales. Random Forest and XGBoost have been shown to be especially effective for forest attribute prediction, with high accuracy and interpretability. Remote sensing imagery, soil information, climate data, and historical management records can be combined with one or more algorithms to provide detailed forest models (Li *et al.* 2020).

Predictive models have been successfully used for forest growth modelling, harvest optimization, carbon sequestration estimation, and climate change impact assessment (Solórzano *et al.* 2022). Several studies have shown that disturbances can be predicted with sufficient accuracy to make operational forest management decisions based on a well-understood disturbance model. The combination of machine learning models and GIS facilitates spatial prediction and scenario analysis for landscape-level forest planning (Gafurov *et al.* 2024).

Applications in forest management

Comprehensive application domains

Big data analytics has found applications across all major domains of forest management, transforming traditional practices and enabling new approaches to forest stewardship. Table 3 summarizes the key application areas.

Forest inventory monitoring

Automated forest inventory systems, using artificial intelligence, have been developed as one of the most mature big data analytics applications in forestry. The systems integrate object detection algorithms, image segmentation methods, and machine learning classifiers to detect and measure individual trees, estimate forest attributes, and produce inventory reports. Presently, these advanced systems allow measurement accuracies similar to standard field-based methods

Table 3. Big data applications in forest management (Stopfer *et al.* 2024, Singh *et al.* 2022, Rossit *et al.* 2019).

Application domain	Big data sources	Data processing methods	Key benefits	Challenges
Forest inventory & monitoring	Satellite imagery, LiDAR, Field surveys	ML classification, Statistical analysis	Accurate resource assessment, Cost reduction	Data integration, Processing capacity
Fire detection & prevention	IoT sensors, Thermal imaging, Weather data	Real-time analytics, Pattern recognition	Early warning, Damage prevention	False alarms, Sensor maintenance
Pest & Disease Management	Hyperspectral imaging, IoT, Field data	Image analysis, Predictive modeling	Timely intervention, Yield protection	Species identification, Early detection
Biodiversity Conservation	Remote sensing, GPS tracking, Camera traps	Spatial analysis, Population modeling	Species protection, Habitat conservation	Data privacy, Species sensitivity
Carbon Sequestration	LiDAR, Satellite data, Ground measurements	Biomass estimation, Time series analysis	Climate mitigation, Carbon trading	Measurement accuracy, Verification
Harvest Planning	GIS data, Market data, Growth models	Optimization algorithms, Simulation	Optimized harvesting, Resource efficiency	Market volatility, Uncertainty
Supply Chain Management	RFID, Blockchain, GPS tracking	Distributed ledger, Data provenance	Traceability, Sustainability verification	Technology adoption, Interoperability
Environmental Impact Assessment	Multi-sensor data, Modeling outputs	Impact modeling, Scenario analysis	Regulatory compliance, Risk management	Data quality, Model validation
Wildlife Habitat Mapping	GPS collars, Remote sensing, Field surveys	Movement analysis, Habitat modeling	Conservation planning, Corridor design	Animal behavior, Technology limitations
Forest Restoration	Historical data, Satellite monitoring	Change detection, Success monitoring	Success monitoring, Adaptive management	Long-term monitoring, Funding
Climate Change Adaptation	Climate models, Long-term monitoring	Climate modeling, Vulnerability assessment	Risk assessment, Adaptive strategies	Uncertainty quantification, Adaptation
Precision Forestry	Multi-sensor integration, AI models	Multi-criteria analysis, Decision support	Site-specific management, Efficiency gains	Technology costs, Skill requirements

while shortening costs and time requirements by orders of magnitude (Xiang *et al.* 2024).

The combination of various data sources such as LiDAR, satellite visualization, and UAV data allows for comprehensive forest inventory systems that can work on multiple scales. New applications of deep reinforcement learning to optimal sampling design and deep generative adversarial networks for data augmentation are also popular. All of these developments are making automated forest inventory increasingly relevant for operational forest management applications (Caspari *et al.* 2020).

Carbon sequestration and climate services

Big data analytics has revolutionized forest carbon monitoring, as it can now deliver precise and cost-effective carbon stock assessments for large geographic areas. Combining LiDAR data and satellite imagery together with the use of machine learning algorithms allows above-ground biomass and carbon storage to be estimated with much greater precision than conventional methods and at a fraction of the cost of field-based approaches (Jiao *et al*. 2023). Time-series analysis of remote sensing data provides a way of tracking carbon stock changes over time that will assist in verifying carbon sequestration projects and climate change mitigation efforts. Automated techniques have been shown to measure and account for changes in carbon stocks that occur as a result of forest management, natural disturbances, and climate variability.

Blockchain and supply chain management

Business assurance and audit trail

Blockchain technology has emerged as a promising tool for increasing transparency and traceability in forest supply chains, solving important problems relating to illegal logging, certification for sustainability, and provenance of products (Stopfer *et al.* 2024). It can be used to provide an immutable record of forest product transactions from harvest to processing to end use. This technology can serve as a means of verification of the sustainability of forest management practices and empower the consumer to have confidence in the traceability of wood products.

Studies have shown the success of blockchain systems for fighting illegal timber trade and advocates of forest certification programs (European Environment Agency 2025). The convergence of IoT sensors, GPS tracking, and digital identification technologies with blockchain has enabled the development of end-to-end traceability systems that can track forest products across the supply chain. These systems include the possibility for real-time verification of sustainability claims, as well as for premium pricing of certified sustainable products.

Carbon credit verification

Blockchain technology has the potential to improve the credibility and efficiency of forest carbon credit markets by providing transparent and verifiable records of carbon sequestration activities. Smart contracts can be employed to automate the validation and trading of carbon credits based on verified carbon measurements and monitored forest conditions. This automation cuts down transaction costs and raises the confidence in forest carbon projects by the market.

The combination of remote sensing and IoT data along with blockchain verification offers full-fledged carbon accounting systems suitable for implementation in large-scale forest carbon projects. Prototype systems that automatically track forest carbon stocks, validate sequestration activities, and generate tradeable carbon credits have been successfully demonstrated. As carbon markets continue to grow, blockchain-based verification systems are likely to play increasingly important roles in forest carbon finance (Boumaiza *et al*. 2024).

Regional implementation and performance analysis

Global implementation trends

The adoption of big data analytics in forestry varies significantly across different regions, reflecting differences in technological infrastructure, investment capacity, and regulatory frameworks. Table 4 summarizes regional implementation patterns.

Table 4. Regional implementation of big data analytics in forestry (Fassnacht *et al.* 2024, Jing *et al.* 2023).

Region	Big Data adoption rate (%)	Primary technologies	Investment level (Million USD)	Key challenges	Future growth potential
North America	78	Remote Sensing, LiDAR, Cloud computing	450	Data integration, Skills gap	High
Europe	72	IoT, Machine Learning, GIS	380	Regulatory compliance, Privacy	High
Asia-Pacific	68	AI, Deep Learning, Remote Sensing	520	Technology costs, Infrastructure	Very High
South America	45	Satellite Monitoring, GIS	120	Funding limitations, Technical expertise	Medium
Africa	32	Mobile IoT, Basic Analytics	85	Infrastructure, Digital divide	High
Middle East	38	Satellite Monitoring, Cloud Computing	95	Water scarcity, Technology access	Medium

Performance comparison

The transformation from traditional forest management methods to big data analytics approaches has resulted in significant performance improvements across multiple metrics. Table 5 compares traditional methods with big data analytics approaches.

Challenges and limitations

Technical and infrastructure challenges

The implementation of big data analytics in forestry is

Table 5. Performance comparison - traditional vs big data analytics methods (Zou *et al.* 2019, Rossit *et al.* 2019, Estrada *et al.* 2023).

Performance metric	Traditional methods	Big data analytics	Improvement Factor
Data Processing Speed	Low (Manual processing)	Very High (Automated processing)	10-100x
Storage Capacity	Limited (Local storage)	Unlimited (Cloud storage)	Unlimited
Real-time Analysis	Very Low (Manual observation)	High (Automated monitoring)	50-1000x
Scalability	Poor (Resource dependent)	Excellent (Cloud-based)	10-50x
Cost Efficiency	High (Labor intensive)	Medium (Technology investment)	2-5x
Accuracy	Variable (Human error prone)	High (AI-driven precision)	2-10x
User Accessibility	Limited (Expert dependent)	High (Web-based platforms)	5-20x
Integration Capability	Poor (Isolated systems)	Excellent (API integration)	10-100x
Maintenance Requirements	High (Equipment maintenance)	Low (Automated systems)	5-10x
Environmental Impact	Medium (Field presence required)	Low (Remote monitoring)	3-8x

faced with major technical challenges in terms of the quality of data, processing capacity, and technological infrastructure. Specific forest sites are usually far from electricity and internet connections, which makes it challenging to use state-of-the-art monitoring systems. Data quality issues such as sensor calibration, atmospheric interference, and time inconsistencies can influence the accuracy of analytical results. The merging of information from several sources with varying formats, resolutions, and coordinate systems provides permanent technical challenges.

Large-scale data acquisition and storage produced by modern sensor systems add both substantial computational costs and increasingly specific knowledge skills for their processing. Many forest management organizations do not have the technical infrastructure and human resources required for the implementation of advanced big data systems. The frequency by which we have changed our technological relationships gives rise to difficulties in preserving system compatibility and demands endless investments in technological renewals.

Barriers: economic and social

One of the key obstacles to the adoption of big data in forest management is the lack of upfront investment in big data systems, which can be prohibitive for a number of forest management organizations, especially those that are smaller and at a community-based level. While big data technologies may offer cost savings in the long term, the initial cost of the hardware, software, and training can be prohibitive. Insufficient skilled workforce able to implement and maintain big data systems, especially in rural forest areas, where so many forest operations are situated.

In traditional forest communities, where it has taken generations for local knowledge and practice to serve as the basis for management, it is not always easy for new technologies to be accepted socially. Big data methods must be integrated with traditional ecological knowledge and community-based management systems, which need careful consideration of cultural factors and stakeholder engagement. The potential for technology to lead to declining employment in forest operations raises social issues

that have to be met through retraining and economic transition programs.

Data privacy and security-related issues

Big data systems for forestry are often generating sensitive information on land ownership, forest resources, and management practices that need to be carefully preserved (Zhang *et al.* 2023). The combination of IoT sensors, GPS tracking, and blockchain systems results in comprehensive data sets that might be useful for unauthorized users. Ensuring security of data while maintaining the functionality and accessibility of the system remains an ongoing challenge for the system designer.

Privacy issues are especially important for community-based forest management and indigenous forest territories, where enormous traditional knowledge and cultural practices may be ingrained in forest management data. Data governance frameworks worldwide are necessary for balancing the need to share data for research and management purposes while at the same time maintaining the privacy of individuals. Cybersecurity threats to forest monitoring systems could potentially interfere with key forest management activities or compromise sensitive environmental data.

Future perspectives and research write-ups

New emerging technologies and integration

Future trends and advancements in forestry that can benefit from big data analytics are going to be defined by continuous development of sensor technologies, artificial intelligence, and computing hardware. Emerging technologies such as quantum computing, edge computing, and 5G networks have the potential to improve the speed and capabilities of forest monitoring systems. The integration of multiple sensing platforms, including satellites, UAVs, IoT sensors, and ground-based systems, will enable comprehensive monitoring at multiple scales.

Advances in artificial intelligence, especially in fields like computer vision, natural language processing, and reinforcement learning, will make it possible to analyse forest data in a more sophisticated manner

and make automated choices. The development of explainable AI systems will improve the interpretability and trust mechanism of analytical results that will aid in increasing the adoption of tools guided by artificial intelligence in forest management. Integration of the big data systems with virtual and augmented reality technologies will enable new interfaces for visualization and management of forest data.

Standardization and interoperability

The development of international standards for forest data collection, processing, and sharing will be critical for the development of global forest monitoring and management systems. Standardized data formats, quality control procedures, and analytical methods will make it easier to share and compare data from various regions and organizations. The creation of open data platforms and collaborative structures will help accelerate the development and implementation of big data solutions for forestry.

Interoperability between various big data systems and existing tools used in forest management will be key to widespread adoption. The implementation of standardized APIs and data exchange protocols will make it possible to integrate new technologies with existing systems seamlessly. International support for big data standards and protocols will facilitate big data applications in global forest monitoring and climate change mitigation.

Capacity building and education

The effective use of big data analytics in forestry will require significant investments in education and capacity-building programs. Universities and technical schools need to create curricula that include traditional forestry knowledge, as well as modern data science and technology abilities. Professional development for practicing foresters will be needed to improve skills and knowledge in existing forest organizations.

International cooperation in capacity building will be especially important here for developing countries where ERP may not have the necessary technical expertise or infrastructure. Technology transfer programs, collaborative research efforts, and technical assistance programs can aid in bridging the digital divide within forest management. The emergence of software tools and decision support systems that are easy to use will demystify the technology of big data for managers who do not have a technical background but have an interest in forest management.

CONCLUSION

Big data analytics is a revolutionary force in modern forestry, as it provides unprecedented opportunities for forest monitoring and analysis and management at multiple scales and applications. The combination of remote sensing technologies, IoT sensors, machine learning algorithms, and cloud computing platforms has led to the emergence of powerful tools for tackling future forest management challenges such as climate change adaptation, biodiversity conservation, sustainable resource utilization, and supply chain transparency.

An analysis of the major application areas of forestry and their impacts on biodiversity conservation finds that big data analytics has reached a high level of maturity in some major areas such as forest inventory and monitoring, fire detection and prevention, and assessment of carbon sequestration. Advanced machine learning algorithms can now achieve independent accuracy of 90% or more in forest classification tasks, while Internet of Things (IoT)-based monitoring systems are delivering real-time environmental data to take proactive management intervention. Cloud computing platforms have democratized access to advanced analytical functions, allowing organizations of all sizes to leverage big data technologies for forest management.

The quantitative analysis presented in this review shows substantial improvements in operational efficiency with big data approaches for data processing speed improving by up to 10-100X, real-time analysis capabilities improving by up to 500-1000X, and measurement accuracy improving by up to 5-10X compared to traditional approaches. The analysis of implementation by region shows that while the global average of adoption is steadily increasing, North America and Europe dominate the usage at 78% and 72%, respectively, and emerging markets in Asia-pacific hold the highest potential for growth

of adoption.

Despite all these advances to date, major challenges exist related to considerations such as data integration and system interoperability, technical capacity, and economic accessibility. The success of widespread adoption of big data analytics in forestry will require an ongoing commitment to technological development and standardization efforts and capacity-building programs. International cooperation and knowledge sharing will be particularly important if the benefits of big data technologies are to be accessible to forest managers worldwide.

Looking toward the future, the continuous advancement in artificial intelligence, sensor technologies, and computing infrastructure promises even more possible functionality for forest monitoring and management. The integration of emerging technologies such as quantum computing, edge computing, and advanced AI systems will allow for real-time, smart forest management systems that can adapt to changing conditions and optimize multiple objectives at the same time. The development of forest digital twins and comprehensive decision support systems will offer unprecedented abilities to forest managers for simulation-based planning and adaptive management.

The evidence presented in this review demonstrates the potential of big data analytics to revolutionize forest management in support of more sustainable, efficient, and effective forest resource stewardship. However, unlocking this potential will require a long-term commitment to technological innovations and capacity building and collaborative strategies that combine cutting-edge technologies with traditional forest management knowledge and practices. As global pressures on forest resources continue to mount, the deployment of big data analytics will play an increasingly important role in ensuring the long-term sustainability and resilience of forest ecosystems.

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