

Review

A Digital Twin Architecture for Forest Restoration: Integrating AI, IoT, and Blockchain for Smart Ecosystem Management

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Abstract

Meeting global forest restoration targets by 2030 requires a transition from labor-intensive and opaque practices to scalable, intelligent, and verifiable systems. This paper introduces a cyber-physical digital twin architecture for forest restoration, structured across four layers: (i) a Physical Layer with drones and IoT-enabled sensors for in situ environmental monitoring, (ii) a Data Layer for secure and structured transmission of spatiotemporal data, (iii) an Intelligence Layer applying AI-driven modeling, simulation, and predictive analytics to forecast biomass, biodiversity, and risk, and (iv) an Application Layer providing stakeholder dashboards, milestone-based smart contracts, and automated climate finance flows. Evidence from DroneCoria, Flash Forest, and AirSeed Technologies shows that digital twins can reduce per-tree planting costs from USD 2.00–3.75 to USD 0.11–1.08, while enhancing accuracy, scalability, and community participation. The paper further outlines policy directions for integrating digital MRV systems into the Enhanced Transparency Framework (ETF) and Article 5 of the Paris Agreement. By embedding simulation, automation, and participatory finance into a unified ecosystem, digital twins offer a resilient, interoperable, and climate-aligned pathway for next-generation forest restoration.

Keywords: forest digital twin; biodiversity conservation; carbon sequestration; decentralized finance; climate technology; blockchain; ecosystem monitoring

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1. Introduction

Tropical forests play a pivotal role in the global carbon cycle, acting as a net carbon sink that removed approximately 1.1 ± 0.3 billion metric tons of CO₂ per year from the atmosphere between 2001 and 2019, despite substantial emissions from deforestation and degradation. These forests collectively store over 200 billion metric tons of carbon in their biomass, soils, and dead organic matter, underscoring their importance for climate regulation and biodiversity conservation [1]. These ecosystems host over half of all known tree species globally, including many that are endemic and ecologically irreplaceable [2]. In addition to their extraordinary biodiversity, tropical forests provide essential ecosystem services such as water regulation, soil stabilization, climate moderation, and cultural benefits to local and Indigenous communities. However, the ongoing triple planetary crisis—consisting of climate change, biodiversity loss, and pollution [3]—is intensifying the vulnerability of forest ecosystems worldwide. Tropical forests are particularly at risk, and

with more than 1.4 billion people directly depending on them for their livelihoods, water, food, and energy, these communities face escalating challenges from land degradation, disease, and extreme weather events. Deforestation and forest degradation are major contributors to global carbon emissions and biodiversity decline. In 2022 alone, approximately 6.6 million hectares of forest were lost [4], and over 930 million hectares have been degraded to varying degrees [5]. Extreme climate-related events further underscore the vulnerability of forests. The 2019–2020 Australian mega-fires [6] and recurrent Amazon forest fires [7] illustrate the increasing intensity and frequency of ecological shocks, amplifying the urgency of reversing degradation and investing in large-scale restoration. The degradation of forest ecosystems not only reduces their carbon sequestration potential but also weakens their capacity to buffer climate extremes and sustain livelihoods.

Recognizing this urgency, several international commitments have elevated forest restoration on the global policy agenda. Notably, the Glasgow Leaders' Declaration on Forests and Land Use, adopted at the 26th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP26, UNFCCC) in 2021, gathered more than 140 signatories pledging to halt and reverse forest loss by 2030 [8]. The Paris Agreement of the UNFCCC, though not forest-specific, emphasizes nature-based solutions to limit global warming to well below 2 °C. The UN Decade on Ecosystem Restoration (2021–2030) further frames restoration as a keystone strategy for climate resilience and biodiversity recovery. At the recent COP29 in Baku in 2024, forests were reaffirmed as critical carbon sinks under Article 5 of the Paris Agreement. Negotiators highlighted the importance of aligning nationally determined contributions (NDCs) with verifiable forest restoration outcomes and emerging digital technologies for Monitoring, Reporting, and Verification (MRV) [9]. Furthermore, updated technical dialogues at COP29 acknowledged the need for digital twin technologies, decentralized finance (DeFi), and blockchain-backed forest data systems to ensure transparency, traceability, and equitable benefit-sharing in forest restoration finance [10].

Despite growing policy momentum, significant implementation barriers continue to challenge forest restoration efforts [11]. Traditional approaches remain highly labor-intensive, difficult to scale, and rely on fragmented or inefficient monitoring systems. Mansourian and Stephenson [12] emphasize that monitoring Forest Landscape Restoration remains fragmented and inconsistent, noting that current tools are often ill-suited for capturing both ecological and social dimensions across landscapes and scales. Similarly, limited traceability around progress and outcomes undermines stakeholder trust—including that of funders, governments, and local communities. Without precise data and transparent accountability systems, reaching the 2030 restoration targets at scale remains improbable.

In recent years, digital twin technologies offer a transformative approach to modeling physical systems by creating real-time, virtual replicas that integrate multi-source data with simulation and control logic. These digital twins enable continuous monitoring, performance optimization, and predictive maintenance, with applications ranging from manufacturing and energy to smart cities and natural systems [13]. A digital twin creates a real-time, data-driven virtual replica of a physical system—in this case, forest landscapes—enabling continuous sensing, predictive modeling, adaptive management, and autonomous intervention [13]. When integrated with drones, artificial intelligence (AI), Internet of Things (IoT) sensors, and blockchain technologies—such as smart contracts—which enable DeFi platforms that replicate financial services on blockchain infrastructure [14], digital twins can power a new generation of smart forest ecosystem restoration systems. These systems promise to enhance precision, efficiency, scalability, and transparency across the entire forest restoration lifecycle. A field-scale study using LiDAR-based digital twinning combined with blockchain and AI achieved 95–98% accuracy in

individual-tree reconstruction and demonstrates how the fusion enhances biodiversity monitoring and sustainable forest management [15].

This paper proposes a digital twin framework for forest restoration, drawing on recent advancements in AI, IoT, drones, and blockchain technologies that also underpin emerging Web3 applications—a decentralized internet paradigm. It addresses the urgent need for transparent and scalable restoration solutions by introducing the concept and architecture of a forest digital twin system, analyzing cost–benefit trade-offs relative to traditional methods, and outlining policy recommendations to accelerate adoption. Drawing on research traditions in computer science, the paper follows a problem-driven, design-oriented approach commonly employed in systems and software engineering research, where problem analysis, artifact design, and evaluation planning are combined to ensure both methodological rigor and practical relevance. Methodologically, the work integrates system architecture modeling, comparative cost analysis, and governance design approaches, using evidence from pilot projects, peer-reviewed studies, and emerging digital MRV standards. By bridging technological innovation with ecological and policy imperatives, the proposed framework offers a technically robust and actionable contribution toward achieving the 2030 global forest restoration and climate goals.

2. Urgent Needs for Forest Restoration and Transparent Technologies

The global policy landscape increasingly recognizes forest restoration as an indispensable strategy for climate change mitigation, biodiversity protection, and sustainable land management. However, in the years following the Glasgow agreement, deforestation trends have shown little meaningful decline, underscoring a growing implementation gap. This shortfall highlights the urgent need for transparent, technology-enabled restoration systems that can accelerate progress, ensure traceability, and build trust. Complementary efforts, including the UN Decade on Ecosystem Restoration (2021–2030) and Nationally Determined Contributions (NDCs), have expanded the restoration agenda, yet outcomes remain inadequate relative to the scale of degradation.

Forest loss continues at a rapid pace: in 2022, global tree cover loss reached approximately 6.6 million hectares, including 4.1 million hectares in primary tropical forests, a rate that is 21% higher than what would be needed to stay on track with global restoration goals [4]. Meanwhile, over 930 million hectares of tropical forest have been degraded to varying degrees, compromising their capacity to sequester carbon and support biodiversity [5]. Collins et al. [6] and Deutsch & Fletcher [7] found that climate-induced disturbances, including mega-fires and prolonged droughts, further weaken forest resilience. These trends threaten the viability of the 2030 restoration goals and undermine the role of forests as nature-based solutions under the Paris Agreement [16].

At COP29, held in Baku in 2024, Parties to the UNFCCC emphasized the urgent need to strengthen transparency, accountability, and traceability in forest restoration finance and performance outcomes. In response to these concerns, technical dialogues increasingly spotlighted digital innovations—including digital twins, blockchain-enabled registries, and DeFi platforms—as promising tools to enhance real-time data collection, traceable funding flows, and verifiable ecological results [17,18].

On the other hand, traditional forest restoration methods—predominantly manual tree planting and field-based surveys—struggle to meet contemporary demands for efficiency, scale, and verification. These methods are labor-intensive, expensive, and often result in low survival rates due to poor site selection and limited monitoring [19]. As restoration financing increasingly ties to measurable impacts, such limitations have made traditional practices increasingly incompatible with modern requirements for performance-based funding and carbon credit issuance.

A critical challenge in scaling restoration globally is ensuring the credibility and verifiability of outcomes. With rising investments in nature-based solutions, funders, carbon markets, and governments increasingly demand clear, quantifiable evidence that restoration efforts are generating real ecological benefits. Yet, in many regions, the lack of robust MRV systems—capable of integrating geospatial data, in-field measurements, and decentralized validation frameworks—remains a major bottleneck [20]. This gap in transparent and interoperable data infrastructure not only limits project accountability, but also restricts access to climate finance and results-based payments, undermining long-term restoration outcomes.

To address these persistent limitations in monitoring and verification, emerging digital solutions are gaining traction—most notably, digital twin technologies. A digital twin is a dynamic, data-integrated virtual replica of a physical system—in this case, a forest landscape. By fusing satellite imagery, drone surveillance, sensor networks, and AI-driven analytics, digital twins enable practitioners to simulate, monitor, and optimize forest restoration activities in near real time [21]. These systems enhance accuracy in planning, adaptive management, and provide early warning capabilities for threats such as droughts, fires, or pest outbreaks [22], thereby filling critical gaps in current MRV infrastructure.

Moreover, when paired with blockchain and smart contracts, digital twins become trust-enabling systems. They allow automated payments to be triggered when restoration milestones—such as canopy closure, carbon stock increase, or species survival—are digitally verified, thereby reducing transaction costs and fraud risks [17,18].

3. Digital Twin Architecture for Forest Restoration

The development of the digital twin architecture in this study follows a design-oriented methodology frequently applied in computer science, where complex systems are specified, modeled, and iteratively refined before large-scale deployment. Rather than relying on a single analytical technique, the approach integrates three complementary elements: system architecture modeling to define functional layers and data flows, comparative cost-benefit analysis using operational data from existing restoration projects, and governance modeling to map verification roles, data integrity requirements, and smart contract-based financing mechanisms. This mixed-method, artifact-centered process ensures that the proposed framework is both technically rigorous and grounded in empirical evidence while remaining adaptable to future performance testing and real-world implementation.

3.1. Conceptual Definition of a Digital Twin in Forest Ecosystems

A digital twin is a dynamic, data-integrated virtual model of a physical system that continuously mirrors its real-world counterpart through real-time data streams, simulation capabilities, and feedback loops. In the context of forest ecosystems, a digital twin represents biophysical conditions—such as vegetation growth, soil dynamics, carbon fluxes, and microclimatic variables—by synthesizing data from distributed sensing networks, aerial drone platforms, and remote sensing infrastructure [21].

Forest digital twins enable a cyber-physical feedback loop in which continuous environmental data from the field are ingested by the model, processed by artificial intelligence (AI) algorithms, and used to simulate system responses to both natural and anthropogenic changes. These responses may include projections of biomass accumulation, hydrological shifts, biodiversity trends, or stress signals such as drought or pest outbreaks [22]. This functionality facilitates near real-time decision support, especially in restoration planning, adaptive intervention design, and species selection.

A forest digital twin system typically integrates four interlinked functions, namely (1) real-time sensing via IoT-enabled environmental sensors and drone-based imaging platforms, capturing high-resolution data on soil moisture, canopy density, photosynthetic activity, and other health indicators, (2) predictive modeling through AI and machine learning algorithms trained on spatial-temporal datasets to forecast risk scenarios and ecosystem trajectories ([21,23], (3) simulation modules that allow planners to test alternative restoration or land-use strategies under varied environmental conditions or policy assumptions, and (4) actuation, either autonomous or human-mediated, involving targeted field interventions such as aerial reseedling, fertilization, or thinning—guided by insights from the digital twin.

Importantly, when integrated with blockchain and smart contract infrastructure, digital twins enable transparent and automated financing mechanisms. For instance, verified ecological performance—such as tree planting survival rates, canopy closure, or carbon stock gains—can serve as triggers for milestone-based payments or carbon credit issuance, as recorded immutably on a decentralized ledger [17,18]. This feature reduces verification costs, enhances accountability, and improves funder confidence in nature-based solutions. Early-stage pilots in reforestation and climate finance contexts have already demonstrated the practical viability of digital twin systems to improve restoration precision, reduce costs, and build multi-stakeholder trust in both ecological and financial outcomes [21,22].

3.2. System Components and Interactions

As illustrated in Figure 1, the digital twin system for forest restoration operates through four interconnected layers: the physical environment, data infrastructure, digital twin engine, and application interface. These layers interact through cyber-physical feedback loops that enable continuous sensing, intelligent decision-making, and performance-based financing.

The physical environment layer represents the forest ecosystem, including tree stands, soil conditions, microclimates, and surrounding biodiversity. IoT sensors monitor variables such as soil moisture, temperature, and pH, while drones equipped with multi-spectral cameras provide canopy and land-use data. Satellite imagery complements these inputs by offering spatially extensive observations [21,24]. Together, these technologies constitute the real-time sensing infrastructure and the starting point for downstream data flows.

The data layer structures and transmits information from the field. Networks such as LPWAN [25] and LoRaWAN [26] enable low-energy, long-range data transfer, while edge computing reduces transmission loads in remote areas. Drone and satellite images are geo-tagged and time-stamped before being stored in centralized or distributed repositories, supporting spatiotemporal modeling and adaptive forest management [21].

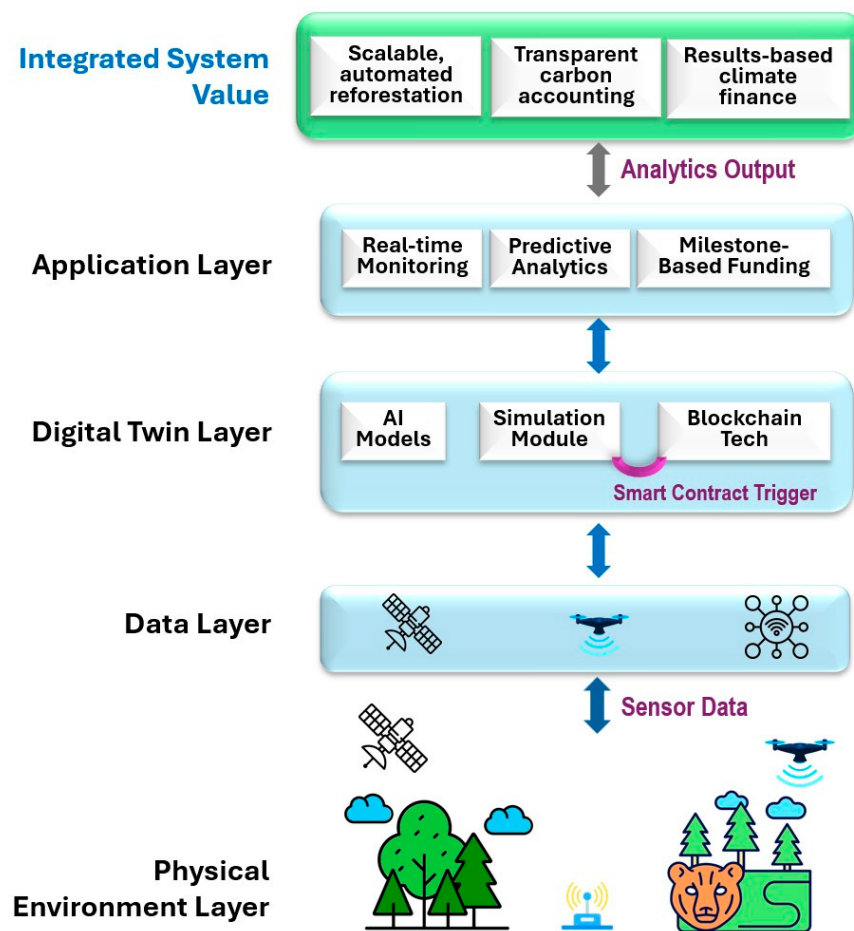


Figure 1. Four-layer digital twin architecture for forest restoration. Data from IoT sensors, drones, and satellites are processed through the Digital Twin Layer to generate predictive insights. Verified outcomes recorded on blockchain trigger milestone-based smart contracts, while the Application Layer delivers monitoring dashboards and finance tools to support scalable and transparent restoration.

At the system's core, the digital twin layer transforms raw data into predictive insights, simulations, and verification outcomes. Machine learning models—including convolutional neural networks and random forest classifiers—analyze imagery and sensor data to forecast biomass, vegetation health, species compatibility, and disturbance risks [22,23]. Simulators generate virtual replicas of forest plots, allowing scenario testing under variable environmental conditions. Blockchain infrastructure records ecological milestones immutably, while smart contracts can trigger automated payments for predefined outcomes such as canopy closure, survival rates, or verified carbon stock increases [17,18]. This integration reduces verification costs and aligns with digital MRV standards such as Verra, ART's REDD+ Environmental Excellence Standard (known as ART-TREES), and the Integrity Council for the Voluntary Carbon Market (ICVCM) Core Carbon Principles [10].

The application layer connects users to system outputs. Dashboards visualize ecological indicators and alerts, while predictive analytics modules provide adaptive planning recommendations. Blockchain-linked funding platforms enable milestone-based financing to be disbursed automatically once outcomes are verified, ensuring transparent decision-making and participatory governance [9].

Feedback loops across these layers maintain responsiveness and integrity. Environmental data flow upward from sensors and drones into the twin, where they are modeled to inform interventions such as drone seeding or precision fertilization. These interventions generate new data that are re-integrated into the system. Financial flows are equally dynamic: once restoration milestones are met, blockchain-based smart contracts trigger disbursements without third-party verification. This closed-loop design ensures the digital twin remains self-updating, transparent, and scalable—providing a credible foundation for large-scale restoration with both ecological and financial accountability.

3.3. Integrated System Value

The integration of the physical environment, data infrastructure, digital twin intelligence, and user-facing applications generates a set of systemic benefits that extend beyond technological novelty. Together, these components create a digitally enabled restoration platform that enhances ecological precision, operational efficiency, financial transparency, and stakeholder trust. One of the most significant values of the system is its ability to scale forest restoration efforts both geographically and operationally. Traditional restoration approaches—reliant on manual labor, periodic monitoring, and centralized oversight—struggle to match the urgency and spatial complexity of the 2030 restoration targets. By contrast, the digital twin system operates as a distributed, sensor-rich network capable of monitoring large and remote forest areas with minimal human intervention. Drones and IoT sensors can be deployed rapidly across restoration zones, collecting data and executing interventions in near real time, thereby enabling faster and more cost-effective implementation [19,21].

In addition to operational efficiency, the digital twin system delivers transparent and verifiable carbon accounting, which is critical for climate finance, compliance markets, avoiding greenwashing, and increasing investor confidence. The integration of blockchain infrastructure and smart contracts ensures that each ecological milestone—such as increases in biomass, verified seedling survival, or enhanced biodiversity—is not only measured but also time-stamped, geo-located, and recorded on an immutable ledger. This transparency significantly reduces the costs and uncertainties associated with third-party verification and enables funders to tie disbursements directly to performance [18]. Such automation aligns with emerging Article 6 rules under the Paris Agreement and supports enhanced transparency reporting under the UNFCCC's Enhanced Transparency Framework [9].

A third layer of value lies in the system's ability to support predictive, adaptive, and inclusive forest management. AI-driven analytics provide foresight on emerging risks, such as droughts, pest outbreaks, or habitat fragmentation, allowing proactive interventions to be implemented before degradation accelerates. Predictive models can also be used to simulate alternative restoration strategies, supporting more robust decision-making under uncertainty [22]. Moreover, the inclusion of open-access dashboards, mobile interfaces, and localized sensor nodes enables participation from a wide range of stakeholders, including indigenous communities, local NGOs, and decentralized restoration actors. These features allow for polycentric governance and promote shared ownership of forest restoration processes and outcomes [27,28].

Finally, the digital twin system creates an enabling environment for milestone-based financing and regenerative economics. By embedding programmable conditions into smart contracts, payments can be tied to ecosystem performance rather than input-based disbursement models. This paradigm reduces overhead, minimizes risks of greenwashing, and incentivizes long-term ecological stewardship. Early pilots from startups such as Dronecoria (www.dronecoria.org/) and Flash Forest (www.flashforest.com) have already demonstrated that drone-based reforestation can reduce planting costs by over 80% and

accelerate deployment up to 25 times faster than manual methods ([19] Oakes et al., 2022). When such efficiencies are coupled with verified ecological performance and transparent financial flows, restoration becomes not only scalable, but investable.

The digital twin architecture represents more than a technical innovation; it is a system-level transformation that supports scalable, transparent, and results-oriented ecosystem restoration. By integrating sensing, modeling, actuation, and financing within a unified feedback loop, the system enables forest restoration initiatives that are scientifically credible, operationally efficient, financially transparent, and socially inclusive. As global institutions seek to operationalize nature-based solutions under the Paris Agreement and the Global Biodiversity Framework, such digital infrastructures will be essential to ensuring that restoration efforts are not only ambitious in scope, but also verifiable, adaptive, and just.

3.4. Example Use Cases and Technology Functions

Recent pilots illustrate how modular digital solutions synergize across the restoration lifecycle. For instance, VTT's forest twin under the EU's Destination Earth initiative deploys satellite, AI, and LiDAR data to assess forest health and carbon dynamics at scale [29]. Similarly, Buonocore et al., [30] present a Forest Digital Twin framework that integrates tree-level sensors, remote sensing inputs, AI analytics, and blockchain-based smart contracts to achieve restoration planning, monitoring, and finance readiness—validated in both site-level and jurisdictional contexts.

Several companies are pioneering the integration of digital twin technologies, drones, AI, and blockchain into forest restoration, demonstrating both scalability and transparency. For example, Flash Forest in Canada deploys drone-mounted seed pod systems capable of planting up to 100,000 pods per operator per day, using machine learning to optimize site selection (erAlberta.ca). AirSeed Technologies (www.airseedtech.com) has achieved deployment rates up to 25 times faster than manual labor [19,21]. Dendra Systems applies aerial mapping and drone dispersal to remote landscapes, though seedling survival rates can be below 20% (www.wired.com). In a digital twin framework, drones not only serve as planting devices but also function as mobile sensors that collect spatial data used to track canopy closure, plant emergence, and vegetation dynamics—data that feeds directly into the twin for real-time modeling and feedback.

Machine learning algorithms—including support vector regression (SVR), artificial neural networks (ANN), and random forest—play a pivotal role in guiding restoration design. For example, SVR and ANN have been successfully used to estimate above- and below-ground biomass of Lebanon cedar stands, yielding more accurate carbon predictions than traditional allometric models [31]. Meanwhile, random forest applied to multi-source remote sensing data in Xinjiang, China, has demonstrated strong accuracy ($R^2 > 0.65$) in biomass estimation and site suitability assessment [32]. These AI-driven models allow restoration planners to simulate multiple scenarios before field implementation, enabling anticipatory rather than reactive decision-making.

Environmental monitoring through IoT networks enhances AI-driven decision-making by supplying continuous, high-frequency sensor data—such as soil moisture, temperature, humidity, and pH—that feed into the digital twin's analytic core. This fusion enables real-time forecasting of growth dynamics, nutrient cycling, and water balance; when thresholds are exceeded, the system can trigger alerts or interventions like drone-assisted irrigation or replanting [33,34].

Smart contract integration via blockchain technologies provides a decentralized, automated mechanism for managing restoration finance. In a digital twin system, verified ecological performance indicators—such as seedling survival, canopy density increases, or satellite-detected carbon stock changes—serve as milestones triggering automatic fund

disbursement [35]. Platforms like the Open Forest Protocol or OFP hereafter (www.open-forestprotocol.org) use blockchain-enabled MRV to issue verifiable credits and maintain immutable audit trails (weforum.org). This level of transparency supports compliance with third-party standards and ensures independent verification by carbon registries, benefiting REDD+, jurisdictional restoration, and Article 6 cooperative approaches [9,10].

Collectively, these examples show that digital twin systems are more than digital replicas—they are operational ecosystems capable of orchestrating autonomous sensing, predictive modeling, adaptive intervention, and milestone-based climate finance. The synergy of drone deployment, IoT sensing, AI analytics, and blockchain validation presents a transformative model for scaling restoration efficiently, verifiably, and inclusively.

4. Cost and Benefit Analysis

4.1. Comparison of Costs and Benefits

The adoption of digital twin systems for forest restoration to meet the global target involves notable upfront investments in hardware, software, and system integration [36]. These costs typically encompass the procurement of drone fleets, environmental IoT sensors, AI processing infrastructure, and blockchain-based platforms for automation and data verification. While such expenditures may initially exceed those of conventional restoration methods, the long-term economic profile of digital systems reveals considerable advantages. Over time, operational efficiency gains, increased automation, and reduced labor dependency lower the total cost of ownership—especially in large-scale or geographically dispersed projects [37].

By contrast, traditional forest restoration methods rely heavily on manual labor for site preparation, planting, and periodic field-based monitoring [38]. These methods tend to incur high recurring costs, are often constrained by workforce availability, and may produce inconsistent ecological outcomes due to limited data-driven targeting. Manual approaches also scale poorly, particularly in the context of ambitious global targets such as those articulated under the UN Decade on Ecosystem Restoration. According to Oakes et al., 19, traditional labor-based programs typically report per-tree planting costs ranging from USD 2.00 to 3.75. In comparison, digital twin technology-enabled systems, such as those employed by Dronecoria (Figure 2), Flash Forest, and AirSeed Technologies, have demonstrated planting costs as low as USD 0.11 per tree, with field deployment speeds up to 25 times faster than manual approaches [19,21].

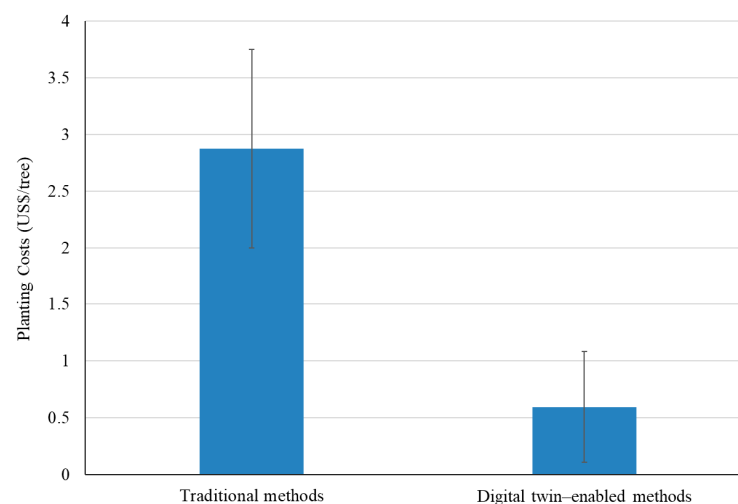


Figure 2. Comparative Cost of Traditional and Digital Restoration Approaches (Average with Min–Max Values).

Beyond the planting phase, digital twin systems unlock additional ecological and financial benefits. Strategically integrated sensors and AI models enable precision species selection based on site-specific microclimatic and edaphic conditions. This functionality contributes to higher survival rates, optimized carbon sequestration potential, and more resilient ecosystem composition over time. Furthermore, real-time monitoring and predictive modeling allow for rapid identification of stressors such as drought, pest outbreaks, or nutrient deficiencies. These features facilitate adaptive management, improving long-term restoration outcomes and reducing the risk of project failure [22].

Financial benefits extend beyond labor and input savings. When integrated with blockchain infrastructure and smart contracts, digital twin systems can reduce transaction and verification costs—particularly in performance-based funding schemes or carbon market mechanisms [39]. Verified ecological milestones, such as increased biomass or canopy density, can be automatically logged on blockchain ledgers, triggering fund disbursements without the need for expensive third-party verification [17]. This level of automation and transparency not only accelerates financial flows but also increases confidence among funders and institutional donors [18].

The social co-benefits of technology-enabled forest restoration are also notable. Digital systems expand local participation through mobile dashboards and inclusive monitoring platforms that enhance transparency and enable co-management [40]. The digitalization of restoration work further contributes to rural job creation in emerging fields such as drone operation, environmental sensor calibration, AI-assisted planning, and decentralized platform governance, providing new employment and capacity-building opportunities in communities implementing UAV-based forest monitoring and participatory technology initiatives [38]. These roles present upskilling opportunities that complement traditional agricultural or forestry employment and strengthen long-term local stewardship [20,22].

A comparative assessment of these trade-offs is summarized in Table 1, highlighting key differences in cost structure, performance, and transparency between traditional and digital twin-enabled forest restoration methods.

Table 1. Standardized cost and performance comparison between traditional and digital twin-enabled forest restoration approaches.

Category	Traditional Methods	Digital Twin-Enabled Methods (with Example Companies)
Initial Investment	Low to moderate (manual labor, hand tools)	High (drones, IoT sensors, AI infrastructure, blockchain systems). Example: Flash Forest's drone fleet and AI seeding platform require significant upfront capital (www.eralberta.ca).
Operational Costs	High (labor-intensive, recurring site visits)	Moderate to low (automated processes, remote monitoring). Example: AirSeed Technologies achieves planting rates up to 25× faster than manual labor, reducing ongoing costs (www.airseedtech.com).
Monitoring & Verification	Infrequent, manual or visual inspections	Real-time, sensor-based, and automated verification [24]. Example: OFP's blockchain MRV ensures tamper-proof, continuous verification (weforum.org).
Carbon Data Accuracy	Low to moderate (aggregate estimates)	High (spatially explicit, sensor-validated, time-stamped) [22].
Trust & Transparency	Moderate (manual reporting, limited auditability)	High (blockchain-based audit trails, smart contracts) [17]. Example: OFP issues verifiable credits tied to blockchain MRV.

Community Engagement	Manual reporting and centralized project oversight	Interactive dashboards and inclusive verification [20,22].
Scalability	Constrained by workforce and logistics	High scalability via autonomous, remotely managed systems [21]. Example: Dendra Systems uses AI-guided drones to restore thousands of hectares annually (www.wired.com).

4.2. Blockchain Governance and Roles

Effective governance is critical for ensuring that digital twin systems for forest restoration operate transparently and reliably. In practice, this requires defining clear roles for participants in the blockchain network and aligning these with institutional responsibilities.

Validators: Entities that maintain consensus on the ledger, such as government agencies, accredited carbon registries, or trusted NGOs. Their role is to confirm the authenticity of ecological milestones and financial transactions.

Data Contributors: Local project developers, community forest groups, and technical providers who collect, preprocess, and submit ecological data (sensor readings, drone imagery, ground plots). Contributors are responsible for ensuring accuracy at the point of data entry.

Auditors: Independent third parties who verify compliance with standards (e.g., Verra, ART-TREES, ICVCM). Auditors can use zero-knowledge proofs and sampling methods to validate data quality without exposing sensitive proprietary information ([41], Man et al., 2025).

Regulators and Financiers: National environmental ministries, donors, and climate finance institutions who rely on the blockchain for real-time monitoring of milestone payments. Their participation anchors the system in existing policy frameworks and ensures alignment with national reporting requirements.

Together, these roles form a permissioned blockchain governance model in which responsibilities are distributed but coordinated. Validators ensure consensus integrity, contributors provide raw ecological inputs, auditors maintain credibility, and regulators/financiers secure institutional legitimacy. This division of labor enhances both transparency and trust while reducing the transaction costs associated with conventional, paper-based MRV processes [17,18].

4.3. DeFi Role and Liquidity Sources

A critical enabler of milestone-based smart contract payments in digital twin-enabled forest restoration is the availability of reliable and timely liquidity. Traditionally, such liquidity is sourced from escrow accounts funded by donors, multilateral climate finance facilities, or private investors. While these channels remain important, decentralized finance (DeFi) protocols present an emerging opportunity to diversify and expand restoration funding. Built on blockchain infrastructure, DeFi protocols utilize smart contracts to automate lending, yield generation, and asset exchange without intermediaries, thereby enabling faster, more transparent, and programmable capital flows [14].

Within this framework, restoration projects can integrate with DeFi liquidity pools to secure pre-committed capital that is automatically released when on-chain verification of ecological milestones—such as canopy closure or verified carbon stock increases—is achieved [39]. Several blockchain-based climate finance platforms illustrate this potential. For example, the OFP enables project developers to measure, report, and verify restoration outcomes on-chain, after which verified carbon credits can be listed on marketplaces such as senken.io (www.senken.io) for global buyers.

This approach creates a continuous funding loop: credits are sold to buyers seeking offsets, revenue flows back into project treasuries, and smart contracts manage disbursements to implementing actors. Such mechanisms reduce dependence on slow-moving grant cycles, enhance investor confidence through immutable audit trails, and align with results-based climate finance principles promoted under Article 6 of the Paris Agreement. Integrating DeFi with digital twin systems therefore has the potential to make restoration finance more scalable, efficient, and resilient to traditional capital market constraints.

4.4. Implementation Roadmap

To translate case study insights into a generalizable framework, we outline an implementation roadmap for digital twin-enabled forest restoration. This roadmap highlights key steps and integration points across hardware, governance, finance, and scaling considerations.

Step 1 Hardware and Data Infrastructure: Deployment begins with IoT sensors (soil moisture, temperature, pH), aerial drones, and satellite inputs calibrated for target ecosystems. Edge devices preprocess field data, which are transmitted via LPWAN or Lo-RaWAN networks to centralized or distributed storage systems ([25,26]).

Step 2 Digital Twin and Governance: Machine learning and ecological simulators generate predictive models of biomass, survival, and disturbance risks. Blockchain infrastructure is implemented as a permissioned network where validators (e.g., government agencies), contributors (e.g., local project developers), and auditors (e.g., NGOs) ensure data integrity and milestone verification [17,18].

Step 3 Finance Integration: Smart contracts are coded to release milestone-based payments (e.g., canopy closure, survival rates) once validated outcomes are reached. Liquidity can be sourced from both traditional institutions and DeFi platforms—such as OFP or tokenized climate finance infrastructure initiatives—providing diversified climate finance channels [42,43].

Step 4 Scaling Pathways: Pilot deployments should start at plot level (10–100 ha) to calibrate models and verify governance mechanisms. Once validated, scaling can extend to jurisdictional or national levels through modular hardware, standardized protocols, and interoperability with existing MRV frameworks (e.g., Verra, ART-TREES, ICVCM).

5. Discussions and Policy Implications

The proposed digital twin architecture offers a promising framework for enhancing transparency, scalability, and efficiency in forest restoration, however, it is not without limitations. A central challenge lies in balancing data transparency and privacy [30,44]. While blockchain and open dashboards can foster trust among stakeholders, private-sector actors may be reluctant to disclose sensitive operational or geospatial data that could reveal competitive information or compromise security ([45], Zwitter & Boisse-Despiaux, 2018). Addressing this tension may require selective disclosure mechanisms, permissioned blockchain architectures, or cryptographic approaches such as zero-knowledge proofs to allow verification without revealing raw data ([18], Liu et al., 2021). In addition, uneven digital infrastructure across regions may hinder adoption, creating a “digital divide” in access to climate finance and advanced monitoring systems, particularly in the Global South ([46], UNEP, 2023).

Another limitation concerns the governance of digital twin systems in multi-stakeholder contexts. For large-scale deployment, digital twins must align with MRV standards under frameworks such as Verra, ART-TREES, and the ICVCM Core Carbon Principles, while also complying with national data regulations and biodiversity monitoring targets. Effective governance requires polycentric and participatory models that involve governments, project developers, and local or Indigenous communities in co-producing

knowledge and ensuring equitable benefit-sharing [27]. Technically, governance depends on clearly defined roles for validators, contributors, auditors, and regulators to ensure accountability, consensus integrity, and institutional legitimacy ([17,18]).

Equally important are risks associated with data quality and integrity. While blockchain provides immutability once data are recorded, it cannot correct errors at the source. Sensor malfunctions, drone limitations, or deliberate manipulation could still compromise reliability. Ensuring data validity therefore requires redundancy, cross-checking, anomaly detection, and independent audits before information is committed to the ledger ([47].

Financial sustainability is another key dimension. Traditional liquidity from donors and climate finance facilities remains essential, but reliance on grant cycles may slow scaling. Integrating DeFi mechanisms provides an additional pathway: projects can access pre-committed liquidity pools, with smart contracts releasing funds upon verified ecological milestones [14,39]. Carbon credit marketplaces, such as senken.io, illustrate how continuous funding loops can be created by reinvesting revenue into project treasuries. While promising, such mechanisms also raise regulatory questions regarding the stability, compliance, and legitimacy of DeFi-based funding, particularly in emerging carbon markets.

From a policy perspective, governments and multilateral bodies play a critical role in embedding digital twin systems within credible restoration frameworks. This includes:

- Establishing interoperability standards for digital MRV to ensure compatibility with national reporting systems.
- Developing legal frameworks that recognize milestone-based smart contract disbursements as valid financial instruments.
- Providing incentives and safeguards to support DeFi integration, while maintaining investor protection and financial stability.
- Encouraging polycentric governance models that give local and Indigenous communities meaningful roles in data provision, validation, and benefit-sharing.

Future research and practice should therefore focus on four priorities: (i) designing governance frameworks that balance transparency, privacy, and participation, (ii) strengthening data validation pipelines to minimize risks of error or manipulation, (iii) testing hybrid finance models that combine DeFi liquidity with traditional funding in scalable, resilient ways, and (iv) conducting systematic performance evaluations to demonstrate the effectiveness of digital twin-enabled restoration. Such evaluations should move beyond conceptual design to measure concrete indicators such as prediction accuracy for biomass or survival estimates, timeliness of verification from field events to on-chain proofs, system reliability under field conditions, and overall cost efficiency compared to conventional MRV practices. Establishing these benchmarks will provide empirical validation, build trust among donors and implementing partners, and ensure that future digital twin systems are not only technically innovative but also operationally proven. Addressing these priorities is critical for transforming digital twin systems from promising pilots into trusted infrastructures for global ecosystem restoration.

6. Conclusions

This paper examined the transformative potential of digital twin technologies in advancing forest restoration amid escalating climate and biodiversity crises. By critiquing the limitations of traditional, labor-intensive restoration methods and systematically assessing recent digital innovations, we proposed a multi-layered architecture that integrates artificial intelligence (AI), Internet of Things (IoT) sensors, unmanned aerial systems (drones), and blockchain infrastructure to support adaptive, transparent, and verifiable ecosystem management. A comparative cost-benefit analysis revealed that although digital systems require higher upfront investment, their long-term advantages—including operational efficiency, greater accuracy in carbon monitoring, enhanced transparency,

and stronger accountability—make them a compelling alternative to conventional approaches. These findings suggest that digital twins can substantially lower the transaction costs of restoration, streamline measurement and reporting processes, and reduce dependence on slow or opaque verification practices.

Digital twins represent more than incremental technological upgrades; they signal a paradigmatic shift in how restoration projects are conceived, monitored, financed, and governed across multiple scales. Their ability to simulate ecological outcomes under different scenarios, enable milestone-based financing through smart contracts, and ensure verifiable data integrity via blockchain fundamentally strengthens the accountability and effectiveness of interventions. When combined with participatory monitoring platforms, these systems create opportunities for community engagement, co-management, and equitable benefit-sharing, helping to bridge the persistent trust gap in climate finance. Real-world examples such as DroneCoria, Flash Forest, and AirSeed demonstrate that digital twin systems are not only technically feasible but also scalable and adaptable across diverse geographies, highlighting their potential to accelerate restoration in both developed economies with advanced digital infrastructure and emerging economies with urgent restoration needs.

To realize this transformative potential, robust enabling conditions and careful attention to social legitimacy are required. High-quality, real-time environmental data, interoperable and transparent modeling frameworks, and diversified liquidity sources must be supported by inclusive governance systems that engage stakeholders from local communities to national policymakers. Significant challenges remain around data transparency and privacy, uneven digital infrastructure across regions, data quality risks linked to sensor and satellite reliability, and the legitimacy of emerging decentralized finance (DeFi) mechanisms. Addressing these challenges will be critical to building systems that are not only technologically advanced but also socially trusted, institutionally embedded, and resilient over the long term. Governments and international institutions should therefore prioritize the development of national digital restoration standards, integrate digital twins into climate finance mechanisms and carbon markets, and invest in cross-sectoral capacity-building to support adoption in the Global South. Future research should also examine governance frameworks that balance transparency and privacy, develop robust data validation pipelines, and explore hybrid finance models that combine decentralized innovations with traditional institutions. Ultimately, digital twins offer a credible pathway toward more accountable, scalable, and inclusive restoration models—aligning ecological ambition with digital innovation and contributing to global ecosystem restoration targets under the Paris Agreement and the UN Decade on Ecosystem Restoration.

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