Forest Management: A Holistic Critical Infrastructure and Key Asset Approach Engaging Satellite View, A.I., Drones and Private Blockchain-Based Decision Support Systems

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Abstract: One of a nation's strategic key assets is its forests. They deserve a perpetual and high degree of care, a sustainable management that requires observation, a legally defensible evidence and integrated intelligence. Given the growing requirements of evidence imposed by European and national silvic frameworks, there is a need to address some struggling approaches like illegal logging, climate induced degradation and a large restoration monitoring.
The conventional forest management frameworks of governance still remain predominantly reactive, relying on providing field inspections, fragmented information systems and outdated declarative reporting.
This article presents an "*in vitro*" digital public system-of-systems infrastructure entitled ForestOS, dedicated to the next generation forest governance and represented in a visual language for GIS based forest Digital Twin of Romania. This proposed architecture is developed as a conceptual governance framework supported by systems engineering principles, geospatial intelligence workflows, AI-assisted risk modeling and permissioned blockchain auditability mechanisms. The article does not present a deployed operational implementation, but defines a reproducible national-scale architecture intended for future pilot validation and institutional testing.
The platform uses satellite and aerial remote sensing, drone-based monitoring and precision afforestation, a natural language model for interacting with an Artificial Intelligence (AI) layer - all with an integrated human-in-the-loop Decision Support System (DSS) and a permissioned blockchain architecture, serving as a fundamental trust layer for institutional accountability, evidence, integrity and non-repudiation.
The Multi-Criteria Decision and Analysis platform ForestOS is designed to early detect loss of canopy as well as many others, like vegetation stress monitoring, detection of tracks of illegal

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transport and objective verification with AI of afforestation and reforestation programs. The results are auditable indicators for environmental, social and governance, together with climate and biodiversity reporting. The ForestOS fundamental architecture represents governance first, human authority, explain ability and legal accountability is augmented in institutional capacity and responsibility.
ForestOS - conceived to create a visual language over a digital public infrastructure, necessary in strategic importance, cadastral systems and national institutional registries. It is designed to establish a unified operational picture of decision makers in all forest-related governance and monitoring authorities. It supports forest protection recommendations as well as restoration within a coherent system. ForestOS is a paradigm shift towards a continuous, intelligence-driven oversight of national forests.
Keywords: SIEM, SOC, NIS2 Directive, Cybersecurity Monitoring, Incident Management, Alert Correlation.

INTRODUCTION: THE GAP BETWEEN ENFORCEMENT AND REFORESTATION

In the Eastern European Carpathian region, forests play a vital role in regulating climate, through carbon sequestration, buffer hydrological and natural extremes, stabilize the soils, and, as well, hosts a large proportion of planetary heritage of terrestrial biodiversity.

Across the European Union and Romania, forests represent a critical economic resource and to the national and European climate commitments (*Păduri | WWF Romania, n.d.; Ultimele Păduri Seculare Din Europa, Mai Bine Protejate | WWF, n.d.*). Forest ecosystems face at the same time persistence pressures from illegal logging, timber laundering, land use changes and climate-driven disturbances such as fire of droughts (*Deforestation in Europe: Where It's Happening and How to Combat It | Fsc.Org, n.d.*). All of these pressures display a structural weakness in traditional forest governance models. The existing forest monitoring systems are predominantly inspection-driven and fragmented across multiple national institutions. The administrative records are outdated and weekly correlated with physical reality, observation being made rather periodic than continuous (*Forest Monitoring - Environment - European Commission, n.d.*).

The characteristic limitation of preserving actions is that evidence is frequently assembled only after violations were suspected. They reduce the effectiveness of informant and critical reforestation programs. A late review of existing AI-driven forest monitoring solutions shows that most systems are conceived to be working as task-specific analytical tools rather than governance infrastructures. The studied literature indicates a lack of standardization, interoperability, explainability and legal traceability, despite advantages in machine learning that already show considerable improvements in the accuracy of forest change detection.

The next generation of forest information systems must be specifically designed to produce auditable, decision-grade intelligence, as these systems are challenging to use in enforcement, compliance, verification and legal proceedings (Buchelt et al., 2024; Kovačovič et al., 2025; Kundu et al., 2025). The existing deployed systems typically lack the mechanisms for a coordinated intervention and post disturbance recovery and present a structured gap between detection, operational action and ecological restoration, even in cases where forest disturbances are discovered (*State of Europe's Forests 2025 Report (SoEF 2025) - FOREST EUROPE, n.d.*)

ForestOS is proposed as an "in vitro" model as a national-scale public infrastructure that reinterprets forest governance. As a continuous and intelligence-driven process by integrating MCDA instruments like spatial truth, layered sensing, AI, and cryptographic natural language tools, the platform ForestOS enables afferent institutions to shift from reactive oversight to predictive and preventive strategies with verifiable governance.

The study specifically investigates:

- the feasibility of perpetual geospatial monitoring at national scale;
- the role of explainable AI in institutional environmental governance;
- the applicability of permissioned blockchain infrastructures for legally defensible environmental evidence;
- and the creation of a taxonomy-driven resilient system-of-systems architecture for forest governance.

Figure 1 represents the perspective of ForestOS on how to view a forest governance framework not as an isolated sectoral process, but as an infrastructure that is able to integrate data classifications and decisions that flow across ecological, economic and national institutional domains.

Figure 1. *Forest Governance as an Integrated Multi Domain System*

State of the art technologies can be used in the main national interests such as biodiversity, forest communities, emerging technologies, forest landscape restoration, forestry and forest products, commodities and supply chains, as well as deforestation and climate change.

Implications for domain security in 2026

Forest monitoring is fundamentally transformed by emerging digital technologies from a periodic reactive activity into a perpetual intelligence-driven process (*Forest Assessment and Monitoring | FAO | Food and Agriculture Organization of the United Nations, n.d.*). Periodical satellite overview of silvic regions combined with AI tools and high-performance computing enables nowadays near real time detection of forest change at a national scale (Roberts et al., 2022).

Massive volumes of satellite imagery data have been made possible due to the advantages of parallel processing and algorithmic efficiency, while modern data visualization tools can translate in neural language interfaces the complex analytics into actionable and editable insights, even for non-specialist decision makers. Law enforcement and local communities can be strengthened with rapid responses by enabling effective alerts via a strong Internet connection or mobile technology.

Landsat, Modis and Sentinel are valuable resources of open satellite-generated data and have succeeded in democratizing access to high-quality imagery, while cloud and smoke limitations are overcome by radar satellites (*Earth Engine Data Catalog - Google for Developers, n.d.*). Future effectiveness of forest management depends on better and more sophisticated AI tools to be able to interpret the growing volume, variety and velocity of silvic-related data.

Forest landscape restoration as a global and national opportunity

For a sustainable economic development and climate-resilient ecological recovery, forest restoration represents a critical layer. More than two billion hectares have been globally identified as suitable and necessary for restoration. The potential scale rivals that of major continental land masses (*Restoration Reports, n.d.*). Critical forest restoration is not only limited to dense silvic regions, but it includes, as well, agroforestry and mosaic landscapes, tailored to ecological conditions. A modern, digitally supported forest restoration platform must be properly designed to enhance ecosystem services, improve food security, mitigate natural disasters and support livelihoods. Its architecture must be ecologically appropriate, avoiding non-native species or excessive tree cover (Brancalion & Holl, 2020).

A major investment opportunity with long term economic returns is represented by reforestation projects as well as from a financial perspective, while at the same time contributing to international commitments such as Sustainable Development Goals (*THE 17 GOALS | Sustainable Development, n.d.*) , The Convention on Biological Diversity (*Home | Convention on Biological Diversity, n.d.*), The Bonn Challenge (The Bonn Challenge | Bonchallenge, n.d.) and the New York Declaration on Forests (*New York Declaration on Forests - Forest Declaration Assessment, n.d.*). Reforestation is positioned both as an environmental necessity and a strategic development pathway.

Illicit forestry, logistics and governance risks

Annually, tens of billions of dollars are lost due to illegal logging within the global forestry economy and this chapter exposes the scale and its complexity, as referred to international illegal logging (*International Illegal Logging: Background and Issues | Congress.Gov | Library of Congress, n.d.*). Illegal practices and unsupervised silvic regions drive deforestation via biodiversity loss, bring an imbalance of greenhouse gas emissions and deprive national governments of revenue and the utility of the national resources. Even simple compliance with existing laws could prevent massive forest loss in national key regions (Araujo et al., 2026).

Effective modern solutions require a coordinated action at the institutional and governmental level, involving as well the civic society and the private sector, law enforcement alone being insufficient. Next generation of national digital forest management instruments are necessary for transparency and verifiable governance mechanisms across the complete forest product life cycle.

Commodities supply chains and zero deforestation commitments

Public-private initiatives and voluntary commitments have set important zero deforestation targets, but their effectiveness depends on precise and transparent monitoring of supply chain impacts (*Corporate Implementation, Impacts, and Reporting on No-Deforestation & "Nature Positive" Post 2020 - Forest Trends, n.d.*). Enhanced tenure data, concession mapping and continuous forest change monitoring enable a more rapid identification of deforestation risks at the sourcing level.

For reducing deforestation, there is a need for presenting complementary mechanisms such as corporate disclosure, certificate schemes, moratoria and jurisdictional approaches (*How the FSC System Works | Forest Stewardship Council, n.d.*). The research organizations and civil society play a crucial role in filling the data gaps where governmental transparency is lacking. A well governed and scalable progress on originally adopted collaborative models that have the purpose to balance environmental protection with economic development.

Deforestation and climate change

This chapter situates deforestation as a major driver of global climate change, responsible for approximately 11% of global greenhouse gas emissions (*5 Ways Deforestation Affects Climate Change | Fsc.Org, n.d.*). Particularly in the tropical regions where forest deforestation is concentrated, the loss of forests undermines climate regulation, biodiversity and livelihood. The global deforestation rates remain very high despite international commitments and mechanisms such as REDD+ and the Paris Agreement.

Next generation land and forest stewardship could deliver up to 30% of the required climate mitigation to meet global recommended temperature targets, making forest protection one of the most cost-effective climate strategies in existence, see Figure 2 (Seddon et al., 2021).

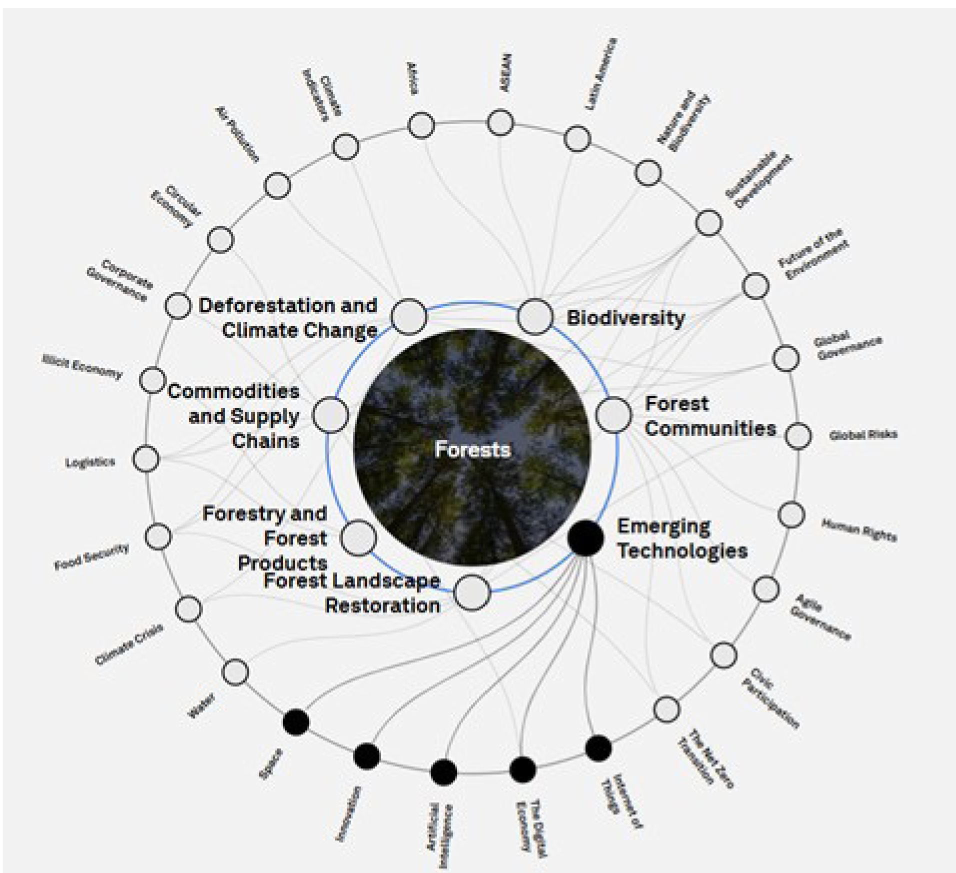

Figure 2. *Technical ecosystem view of digital forest management*

Success requires sustained vigilance, credible monitoring and coordinated actions across governments, national authorities, markets and civil society by translating commitments into measurable and verifiable outcomes (*Strategic Intelligence, n.d.*).

FORESTOS - CONCEPT AND CONTRIBUTION

This particular article is designed to connect in an explicit manner advanced technology with its strategic relevance for national interests. In a systematic structure, it shows how technologies can be methodologically deployed as instruments for digital public governance.

ForestOS does not attempt to compete with existing satellite analytics platforms; instead, it proposes an institutional governance orchestration layer that integrates evidence traceability, AI-supported DSS logic, and cryptographically auditable workflows. To better contextualize this positioning, Table 1 provides a comparative overview of ForestOS against existing forestry monitoring and analytics systems.

Table 1. *System-Level Comparison Across Data, AI, DSS and Governance Layers*

System	Satellite	AI	DSS	Blockchain	Governance Focus	Legal Auditability
(Forest Monitoring, Land Use & Deforestation Trends | Global Forest Watch, n.d.)	YES	Partial	NO	NO	Monitoring	Limited
(Copernicus Land Monitoring Service, n.d.)	YES	Partial	NO	NO	Observation	Limited
(Precision Forestry - Geospatial Forestry Platform - Swift Geospatial, n.d.)	YES	YES	Partial	NO	Operational	Low
ForestOS	YES	YES	YES	YES	Governance	High

The operational philosophy of ForestOS is grounded in the independent principles that together define its fundamental architecture.

- The first principle is spatial truth, being defined by all forest rights, obligations and restrictions. ForestOS therefore treats GIS data as a visualization layer for the authoritative substrate of governance.
- The second principle is the continuous observation. National-scale governance requires a flow of persistent and objective observations. ForestOS implements layered sensing through satellite imagery, SAR and drones.
- The third principle is legally trusted evidence. ForestOS embeds provenance, confidence scoring and cryptographic anchoring across all critical records.

The three described principles ensure institutional legitimacy and that the technology outputs can be used directly in administrative and juridical processes. These foundations distinguish ForestOS from conventional monitoring platforms.

The core contribution of this article is a shift in perspective from detection technologies to the formalization of forest governance, as an auditable and institutionally legitimate digital public key asset infrastructure.

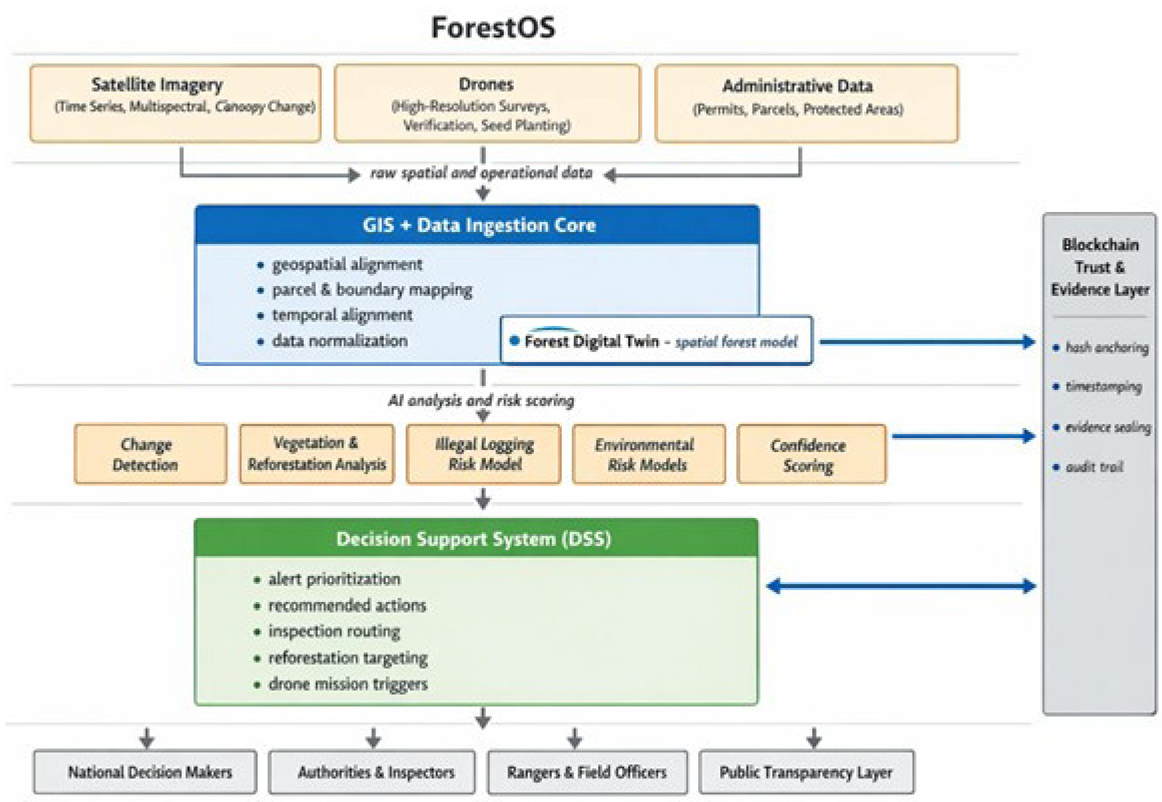

Figure 3. *ForestOS Governance Architecture: from Multi-Source Sensing to Auditable Decisions*

As seen in Figure 3, ForestOS is designed to manage and support national silvic sovereignty while coordinating with European regulatory and policy frameworks. At the national level, ForestOS supports Romanian forest legislation, planning of forest management, national inventory processes and enforces mandates of competent authorities. As well, at the European level, the platform produces geolocated, traceable and auditable evidence, relevant to regulations related to deforestation and European Union Green Deal objectives (*The European Green Deal - European Commission, n.d.*), biodiversity, strategic targets and climate reporting obligations (*Investigations and Inspections, n.d.*).

Figure 3 illustrates an "in vitro" operating architecture of the ForestOS platform, where multisource data, including satellite imagery, drone data and administrative records, are integrated into a GIS data ingestion core that supports the National Forest Digital Twin.

Different AI agentic models operate on top of this layer for detection of changes, vegetation analysis, risk modeling and confidence scoring. The generated results are converted and translated into operational cases through a DSS, which is designed to prioritize alerts and field intervention actions. A private blockchain infrastructure serves as a trust layer and ensures cryptographic anchoring, timestamping and chain of custody, guaranteeing evidence, integrity and institutional decision auditability.

HOW THE FORESTOS SYSTEM SEES: CONTINUOUS GEOSPATIAL MONITORING

The multisource data integration represents a great advantage in forest monitoring because it superiorly increases the detection accuracy, structural characterization and ecological interpretation (Liang et al., 2025). The ForestOS Digital Twin is a living time-aware digital model of the Romanian National Forest Fund (Buonocore et al., 2022). Each parcel of the forest exists simultaneously as a physical ecosystem, a spatial object and a regionally governed entity.

The institutional and authoritative layers include cadastral boundaries, forest compartments, management plants, inventory and attributes, protected areas, road networks, hydrology and terrain models. All incoming data is aligned in a special manner, so this foundational reconstruction of historical states is enabled through temporal visioning, a fact that allows causal analysis of any changes and also supports long term assessment of restoration success.

The Digital Twin layer serves as a single source of spatial truth, ensuring consistency across the national institutions and authorities and it enables a direct correlation between permits and physical reality. It essentially provides a basis for all analytics and decision support. Forest structure and condition are being continuously updated through sequential data ingestion. The typical pipelines for processing include data acquisition and geometric and radiometric correction. Through high-resolution satellite imagery, individual tree crowns are segmented into operational patterns. An AI-based classification is constantly applied over time for the monitoring of the forest funds. The progression of disturbances can be observed and afferent recovery trajectories can be assessed. Through this specific process, static GIS maps are transformed into living digital representations of national silvic ecosystems (Abreu-Dias et al., 2025).

The primary observation backbone of ForestOS constitutes the remote sensing, providing the perpetual objective measurement capabilities required for national-scale forest governance. Some of the elements that the platform integrates are optical multispectral satellites, synthetic aperture radar (SAR) and spaceborne LiDAR technology to capture detailed complementary aspects of the forest condition, structure and dynamics.

Open satellite data programs like Landsat, MODIS and the European Sentinel constellation, together with high-resolution commercial satellites, enable unprecedented temporal frequency and spatial detail for forest observation and Multi-Criteria Decision Analysis suggestions.

For the detection of canopy change, vegetation vigor and phenomenological patterns, optical multispectral satellites like Sentinel 2 and Landsat are able to provide high-frequency, medium and high-resolution imagery (Torres et al., 2021). A red-edge and near-infrared bands enable estimation of chlorophyll content and leaf area proxies, while shortwave infrared bands support moisture and disturbance detection (Misra et al., 2020).

ForestOS allows, through time-series analysis of those signals, to identify gradual degradation, abrupt disturbances and necessary trajectories for recovery. Sentinel 1 SAR imagery provides all-weather observation capability day and night, overcoming cloud and smoke limitations that historically constrained forest monitoring. SAR backscatter and coherence features contribute to disturbance detection, soil moisture estimation and landslide for flood context, strengthening situational awareness, see Figure 4 (Canisius et al., 2019).

Special spaceborne LiDAR missions provide 3D measurements of the heights of the canopy and vertical forest structure (Bolcek et al., 2025). This fact improves biomass and carbon stack estimation and enhances calibration of models that are satellite-based. LIDAR-derived structural metrics are important and valuable for assessing forest maturity and restoration success.

ForestOS implements pipelines for preprocessing that perform atmospheric correction, masking of clouds and shadows, radiometric normalization, co-registration and quality scoring. Outputs are stored as analysis-ready data and indexed for spatial-temporal querying.

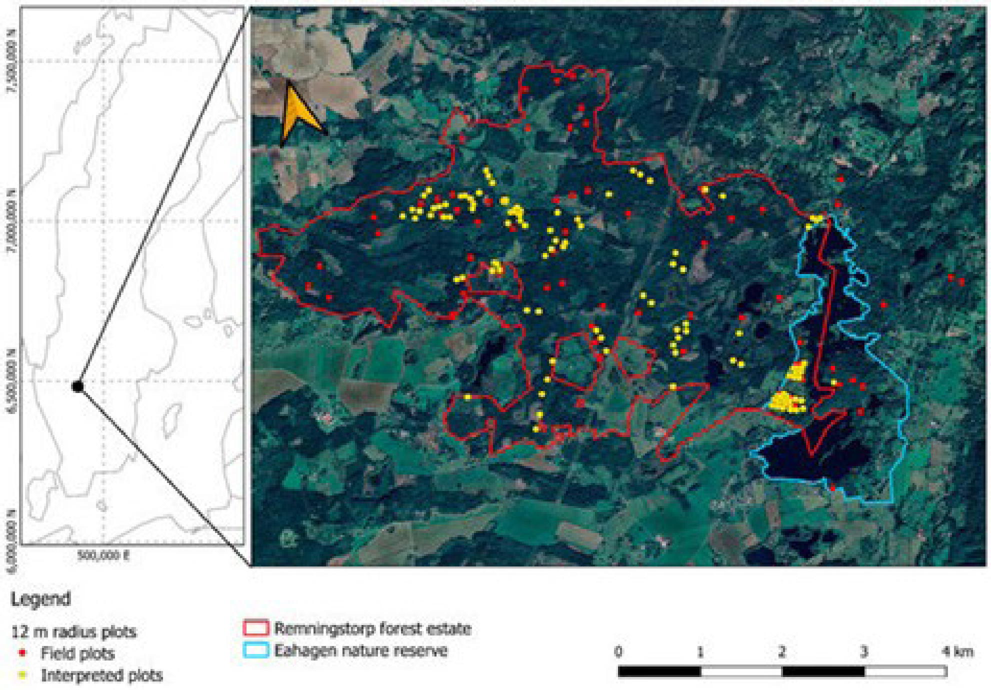

Figure 4. *SAR imagery for forest monitoring*

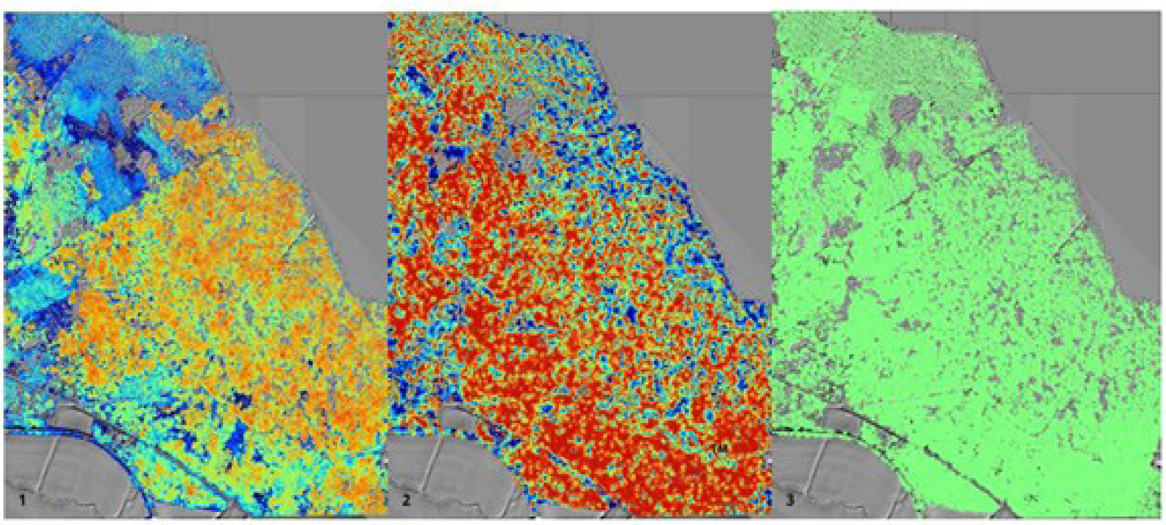

Figure 1: 1) Forest canopy height: Tree heights are color-coded (blue to red) according to the height above ground. 2) Crown coverage map: The terrain is colored by the percentage of vegetation coverage. 3) Vegetation mask: Areas of vegetation 3m and above, exceeding 10 sq m.

Figure 5. *Forest complexity and multispectral analysis*

In Figure 5, ForestOS remote sensing analytics are designed as complex probabilistic indicators, rather than deterministic facts. Signals derived from satellites are systematically correlated with historical patterns, management plans and permit data before governance action is recommended.

To ensure that the model performance remains reliable, a continuous validation against drone and field observation is needed. To enable ForestOS to evolve, retraining cycles must be institutionally governed. As remote sensing evolves, it becomes more than a data source, it turns into a continuously improving national observation capability.

Proposed Technical Implementation

ForestOS follows a modular architecture organized into geospatial processing, remote sensing ingestion, AI analytics, decision support and trust infrastructure layers, detailed in the sections below.

A. Core Technology Stack

- **Geospatial Layer** - PostgreSQL + PostGIS for spatial data management, with GeoServer for OGC-compliant map services.
- **Remote Sensing Layer** - Satellite data ingestion via Sentinel Hub, with Copernicus data sources for multispectral and SAR imagery.
- **AI Layer** - PyTorch-based models for forest segmentation, change detection, and risk scoring, supported by TensorFlow inference services where needed.
- **DSS (Decision Support System) Layer** - Backend services (FastAPI) and dashboard interfaces (React/Next.js) for case management, alert aggregation, and role-based decision support.
- **Blockchain Layer** - Hyperledger Fabric for immutable logging of validated cases, inspection results, and audit events via cryptographic hashing.
- **Storage Layer** - S3-compatible object storage (e.g., MinIO) for satellite imagery, UAV data, and AI outputs, combined with PostGIS for structured geospatial data.

B. Data Pipeline

- Satellite data ingestion via Sentinel Hub;
- Preprocessing (cloud masking, normalization, geo-referencing);
- AI inference for anomaly detection and risk scoring;
- DSS (Decision Support System) transformation into structured case objects;
- Blockchain anchoring of validated records.

C. Infrastructure

- Kubernetes-based deployment for microservices orchestration;
- Event-driven architecture (Kafka-based pipelines);
- Containerized services (Docker);
- Centralized monitoring (Prometheus / Grafana),

D. Security & Access

- Keycloak-based identity management (OAuth2 / OIDC);
- Role-Based Access Control (RBAC);
- TLS encryption for inter-service communication;
- Audit logging for all operational actions.

HOW THE SYSTEM THINKS: AI DETECTION AND RISK REASONING

AI is the operational brain of the platform ForestOS. The architecture transforms heterogeneous data streams into explainable and actionable intelligence that supports governance. AI technologies, including adaptive neural networks, Random Forests and Support Vector Machines, are increasingly applied to forest change detection and identification of anomalies (Kovačovič et al., 2025; Kundu et al., 2025).

These AI-supported models enable an automated recognition of deforestation events and disturbances of the canopy from remotely sensed data.

A reliable performance remains highly dependent on data quality, configuration of sensors and the training of sample representativeness. In applying these settings of the system, thousands of labeled Unmanned Aerial Vehicle (UAV) and satellite images are usually required. This is necessary to achieve reliable detection of maintenance outcomes. These requirements underscore that the curation and validation of data are foundational governance tasks (Abreu-Dias et al., 2025; "How Drones and AI Are Making Forests More Valuable | Riga Technical University," n.d.).

Within the ForestOS platform, AI models operate across multiple spatial and temporal levels. Satellite and SAR time-series are analyzed at the landscape scale to detect canopy gain or loss and vegetation stress. At stand and tree scale, they process drone imagery to assess forest density, early stage stress and survival rates. Optional forensic models are able to identify wood species from microscopic imagery, supporting downstream traceability.

The core analytical functions of ForestOS include forest change detection, vegetation health analysis, illegal logging risk prediction, transport anomaly detection, verification and planning of afforestation. As well environmental risk forecasting, such as fire, erosion, drought or landslide susceptibility.

As seen in Figure 6, the platform uses hybrid modeling strategies by combining machine learning, deep learning and rule-based logic. This kind of approach increases robustness in different contexts where labeled data is limited and ensures alignment with legal constraints. All outputs of the AI are probabilistic and accompanied by confidence scores. Explainability is mandatory so that rule traces, feature attributions and model recession are preserved.

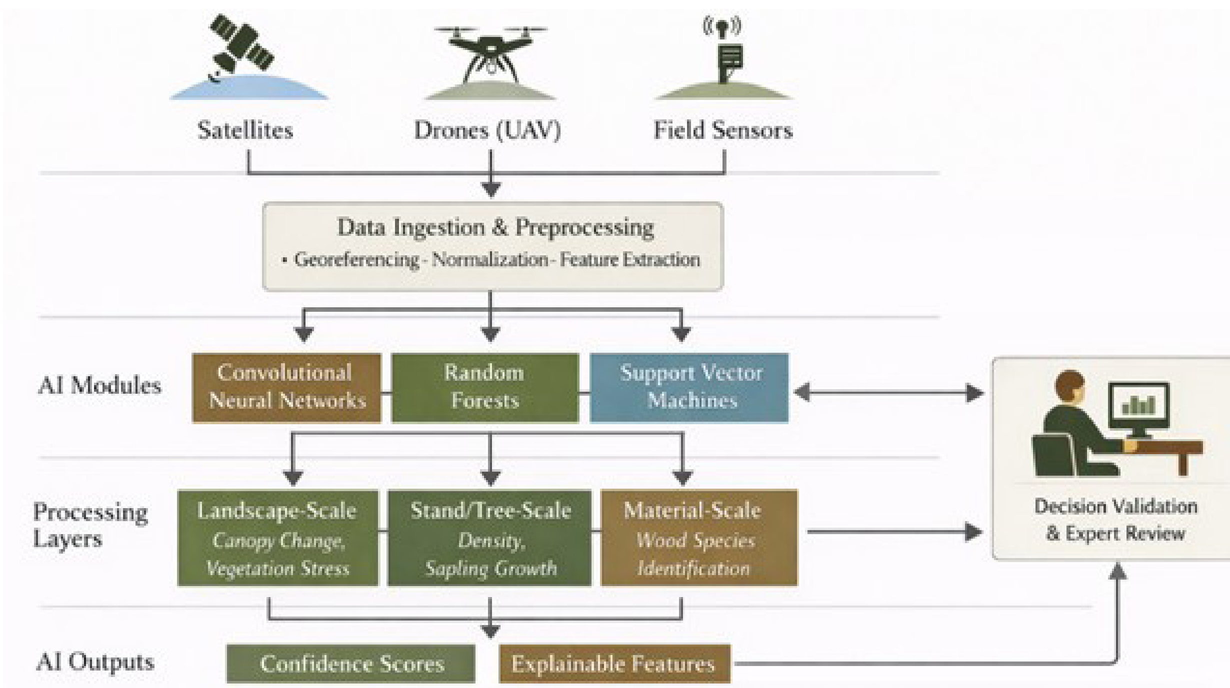

Figure 6. *Multilayer operational architecture integrating remote sensing, AI analytics, DSS orchestration and blockchain evidence anchoring*

By dynamically adjusting confidence thresholds based on contextual feedback, AI approaches improve recall and adaptability in deforestation detection. The performance of the platform remains sensitive to the quality of the data and class imbalances, highlighting the necessity for explicit uncertainty modeling in those that are governance-oriented (Kundu et al., 2025).

AI models are subject to lifecycle governance. Training datasets, parameters and performance metrics are carefully documented and analyzed. Drift detection monitors the forest degradation over time. Retaining and updates are constantly reviewed before deployment.

AI does not issue binding decisions, but rather supports human decision-making by structuring information and highlighting risk.

HOW THE SYSTEM ACTS: DECISION SUPPORT AND FIELD WORKFLOWS

The DSS represents the cognitive layer of ForestOS. This layer converts analytical outputs into operationally usable governance actions. The DSS layer actively structures information, reduces uncertainty and supports consistent risk-based decision making across institutions. As well, the DSS layer aggregates alerts from satellite analytics, aerial drone observations and AI services into unified case objects.

Every case of observations contains special context, temporal history, risk scores, indicators of confidence and evidence links. The ForestOS cases are automatically prioritized by using multi-criteria ranking, incorporating probability of illegal actions, eventual potential ecological impact, proximity to protected areas and historical noncompliance patterns.

By design, the platform has a built-in human-in-the-loop architecture, so that human operators always retain the final authority. The DSS layer supports judgment, not replaces it. All approvals, rejections and modifications are immutably logged on a governmental private blockchain infrastructure.

ForestOS provides at the operational level real-time situational awareness of silvic regions' conditions, inspection status, drone missions, restoration programs and activities for transport monitoring. At the national and on request, international level, authorities access consistent information about the forests derived from the same foundational evidence base. As presented in Figure 7, the platform's dashboard displays the active key indicators and alerts.

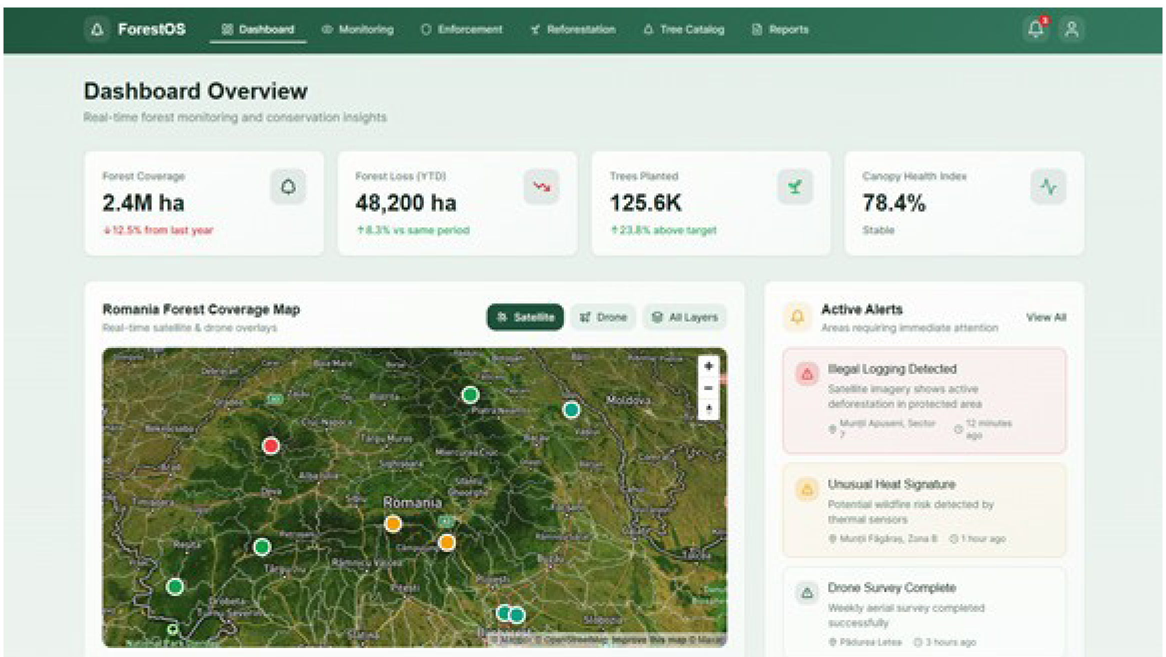

Figure 7. *Overview of ForestOS operational dashboard*

At the coordination level, cross-agency collaboration is fully supported. Authorized users from diverse authorities are able to access relevant shared case studies, evidence, references and intervention timelines. The personalized and role-based access control sustains the confidentiality of institutional mandates.

The platform is as well suited to specific governance functions. It monitors satellite imagery, data volumes and drone fleet availability, data latency and the performance of different AI models. An early detection of degradation of the forest is routed to the entire system, preventing quiet failure of downstream and analytics.

The effective deployment of ForestOS depends on institutional capacity and human expertise rather than on technological integration. Human personnel like inspectors, analysts and decision makers must be trained to handle and interpret probabilistic outputs, assess confidence scores and exercise judgment under uncertainty.

HOW THE SYSTEM RESTORES: DRONE ENABLED REFORESTATION INTELLIGENCE

Industrial usage of autonomous drones equipped with AI and LiDAR technologies is able to analyze burnt or degraded terrain, assess soil composition, moisture composition, slope and erosion risks and can be used for deployment of biodegradable seed pods, containing native seeds with nutrients and fungi (Such et al., 2023).

AI model-based programs that manage individual drones to deploy hundreds of pods per reforestation covering areas equivalent to a football field within an hour, through swarm-based operations. A persistent large-scale restoration mission is maintained through solar-assisted recharging infrastructure.

For silvic areas restoration, ForestOS treats UAV seeding as probabilistic interventions embedded with an AI-monitored trajectory grid. According to empirical studies, it is indicated that establishment rates may widely vary depending on site conditions, see Figure 8 (Crouzeilles et al., 2016). The workflow is therefore integrated with over-seeding, adaptive prescriptions and follow up verification.

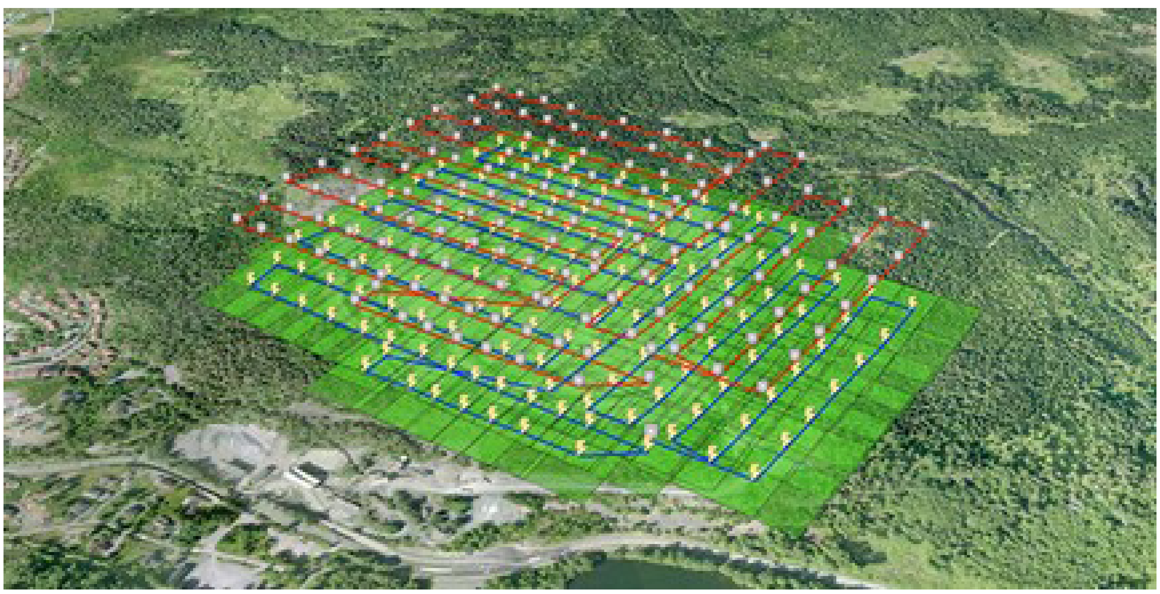

Figure 8. *Digital mapping of drone-based reforestation mission*

Monitoring with satellite imagery the silvic areas that are visible as being restored, as well as with drones and computer vision, allows objective measurement of forest density and mortality, while evaluating the quality of maintenance at scale.

Very important for a healthy forest establishment, the first two to three years are relevant. During this period, young tree areas need to be actively managed to control overgrowth, detect dead saplings and adjust management practices ("How Drones and AI Are Making Forests More Valuable | Riga Technical University," n.d.).

Planting data, as well as enhanced information about the species and planting methods, is also centralized in private blockchain databases and displayed in ForestOS dashboard, as seen in Figure 9.

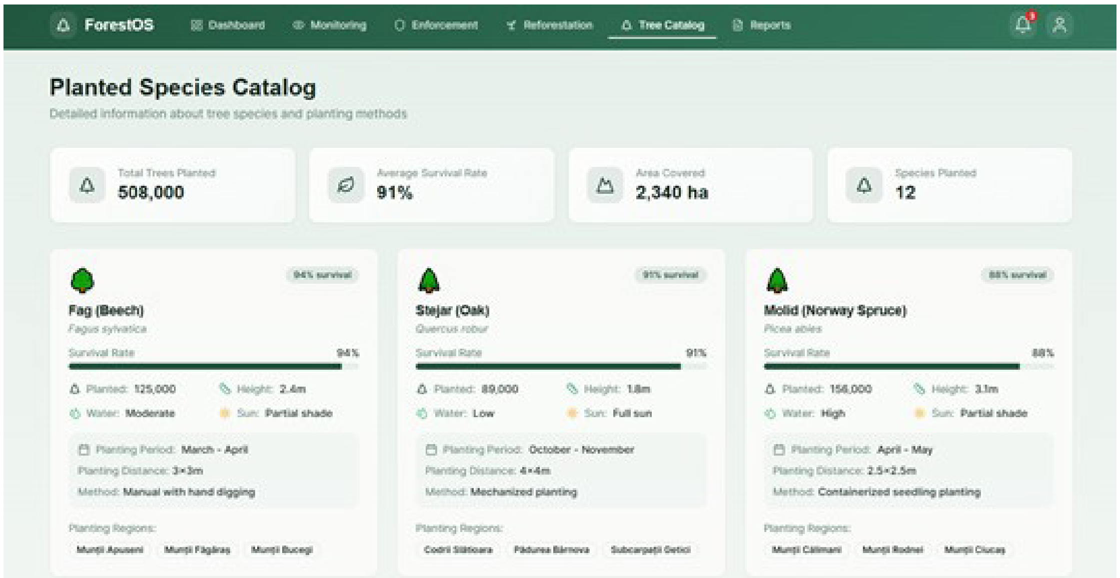

Figure 9. *ForestOS centralized planting data and species information*

The platform combines AI-based scenarios that manage site sustainability modeling, prescription versioning, UAV deployments and post deployment logging through satellite and drone imagery.

ForestOS converts emerging drone reforestation technologies into a governance-grade capability where each log of deployment activities is traceable, verifiable and available against measurable ecological outcomes.

Figure 10. *Advanced AI-driven reforestation workflow*

As visible in Figure 10, the advanced reforestation workflow is designed to have five phases in which technologies and technical components are embedded. The following results are being monitored, namely: Analysis, Planning, Action, Verification and Certification.

Phase One – Analysis: The integrated reforestation architecture of ForestOS is visualized and represents a new method of operatizing silvic areas restoration through the use of AI, aerial and decentralized technologies, specifically data-driven workflows from start to finish.

The digital silvic ecosystem management begins with a special assessment of the areas needing to be restored through a detailed diagnostic phase. Along this initial phase, satellite data from remote sensing products offered by afferent agencies are used to recognize and geographically identify degraded or low-performing areas of forests through gap analysis. Time series and multi-spectral datasets are internally used to identify zones in need of priority interventions, based on vegetation indices, land use challenges and evidence of ecological sensitivity.

Phase Two – Planning: After carefully going through the Analysis phase of evidence-based assessments, the functionality of the planning phase incorporates machine learning models to enhance the selection of proper species, determine the appropriate habitat and provide the necessary instruments to match those species with their ideal ecological and area-specific soil characteristics.

For a successful establishment of certain tree species at the designated forest sites and the determination of predicted climate scenarios, there is a need for the development of predictive algorithms for AI models for factoring existing natural conditions such as soil characteristics, climate, topography and land use. As well, for a better chance of long-term ecosystem resilience and stability, the use of modern technology will transition to a natural species selection based on statistical probability for optimization.

Phase Three – Action: Once the Planning phase is complete and digitally enabled, the Action phase represents the implementation in the field. This phase will be accomplished by using special drones equipped with pneumatic delivery modes and airborne plant biodegradable pods in locations within range capabilities, which might be traditionally too remote for access on the ground, or too cost-prohibitive to implement by conventional planting methods.

Modern precision forestry methods are used to adaptively modify the spacing, density and soil type in a planting area by determining where micro-sized differences may occur. This approach increases the chance that the plants will grow successfully and in a natural, ideal manner and it ensures that resources are used efficiently.

Phase 4 – Verification: After the Action phase, the Verification phase relies on time series satellite scanning to monitor changes to the forest after a reforestation mission has taken place. Change detection algorithms and measurements of the vegetation provide important data for assessing how well recovery is taking place, estimating the rates of survival of silvic areas and measuring canopy growth and biomass.

Phase 5 – Certification: The final phase is the certification of reforestation missions, which provides a governance layer by leveraging smart contracts and distributed layer technology (private blockchain). Verified ecological performance indicators are securely and encrypted by being saved on digital immutable records, allowing the automation of compliance checks and clear institutional auditing.

Empirical studies also indicate that established rates can vary significantly depending on area conditions, sometimes falling below 20% in unfavorable contexts (Korbik et al., 2025). ForestOS treats a probabilistic drone intervention as embedded within a monitored trajectory, based on relief and surface conditions of the site.

Overseeding, adaptive prescriptions and follow-up verifications are integrated into the ForestOS workflow. The platform operationalizes this reality by combining AI-based site suitability modeling, prescription versioning, UAV deployment logging and post-deployment monitoring through satellite and drone imagery. ForestOS converts emerging technologies adapted from drone reforestation into a governance grade capability.

The indicators in Table 2 define the target evaluation framework for ForestOS pilot deployment. These metrics represent preliminary performance targets for system validation and do not constitute experimentally validated benchmarks.

Table 2. *Operational Performance Metrics*

Metric	Target
Detection latency	< 24h
AI confidence threshold	> 92%
Drone verification time	< 12h
Evidence anchoring time	< 5 min
Restoration monitoring frequency	Monthly

HOW THE SYSTEM PROVES EVIDENCE, TRUST AND AUDITABILITY

Post reforestation monitoring remains essential for validating reforestation success. Aerial imagery like satellite data combined with AI based analytics allows a perpetual assessment of seeding survival, vegetation development and identify early stress indicators.

This kind of approach provides a reliable basis for verifying the forest restoration results. When correctly integrated with field measurements, as well adjusting management strategies over time is an imperative prerogative for decision makers.

ForestOS employs private blockchain technology. It preserves a specialized trust infrastructure for anchoring institutional high value governance facts for securing the integrity of evidence over longtime horizons. The blockchain layer is intentionally narrow in scope and it serves as an institutional cryptographic notary and evidence registry for legally relevant records. It does not attempt to store large datasets or replace operational databases, see Figure 11.

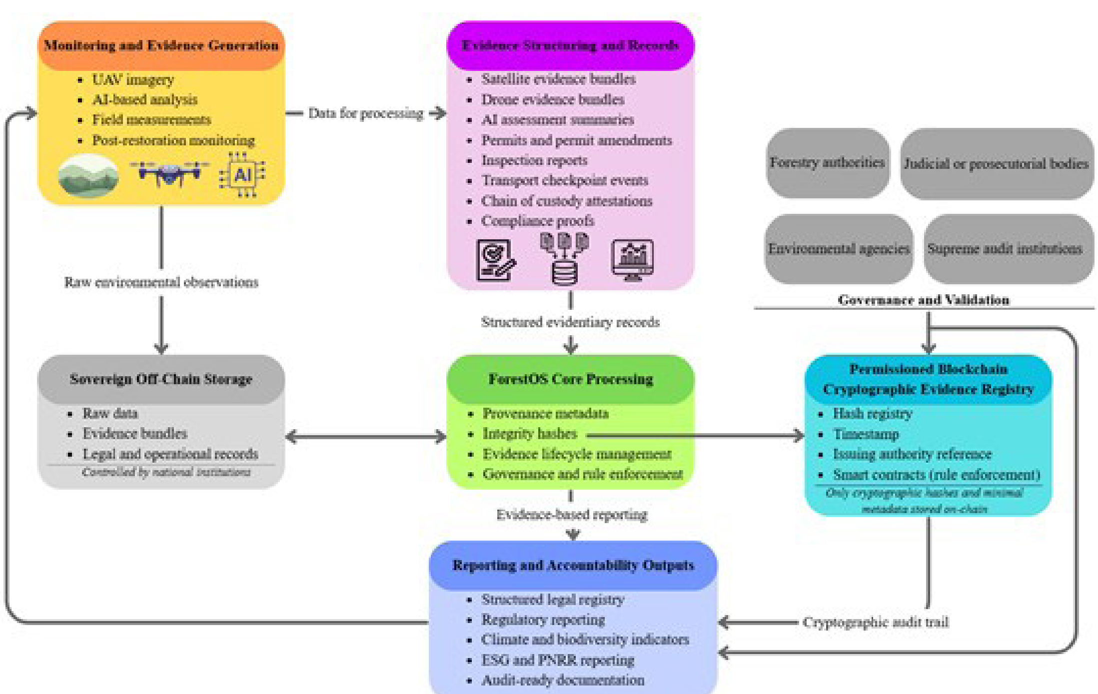

Figure 11. *Technical flow of the ForestOS system architecture*

On-chain, there will be anchored only the cryptographic hashes and minimal metadata of critical records. National institutions will control sensitive raw data that remains in sovereign off-chain storage. The anchored items will include satellite and drone evidence bundles, AI assessment summaries, permits and permit amendments, report of inspections, transport checkpoint events, chain of custody attestations and compliance proof for afforestation and reforestation programs.

Every record that will be anchored on-chain is associated with immutable data such as timestamp, issuing authority and reference to its off-chain storage location. Only authorized parties are allowed to recompute the hash from the original data and verify its correspondence with the on-chain anchor. In this way, integrity and authenticity are provided.

It is worth noting that permissioned governance defines which institutions or authorities are authorized to submit anchors, validate transactions and audit records. Validator nodes may be operated by forestry authorities, environmental agencies, supreme audit institutions like ministries and juridical or prosecutorial bodies. This model of distributed validation prevents centralized manipulation and leads to institutional trust.

The governance logic is directly embedded through customized smart contracts into the evidence life cycle, i.e., a harvest-related evidence anchor cannot be accepted unless a varied permit anchor exists.

The anchors of the forest restoration outcomes must reference a baseline anchor. The transport checkpoints' anchors must reference a declared source parcel and an active legal transport authorization. These rules mirror juridical requirements and enforce consistency at the technical layer.

ForestOS aligns private blockchain usage with digital forensics best practices. Every evidence bundle includes provenance metadata, chain of custody records and integrity hashes. Anchoring these hashes on-chain, it adds an additional layer of non-repudiation and timestamping, strengthening admissibility and administrative legal proceedings.

Beyond enforcement, the blockchain layer provides audit and institutional accountability. Auditors are able to independently verify that reported indicators and compliance chains correspond to institutional blockchain-anchored evidence.

The audit and accountability capabilities of ForestOS are operationalized via a dedicated reporting and documentation interface, as presented in Figure 12.

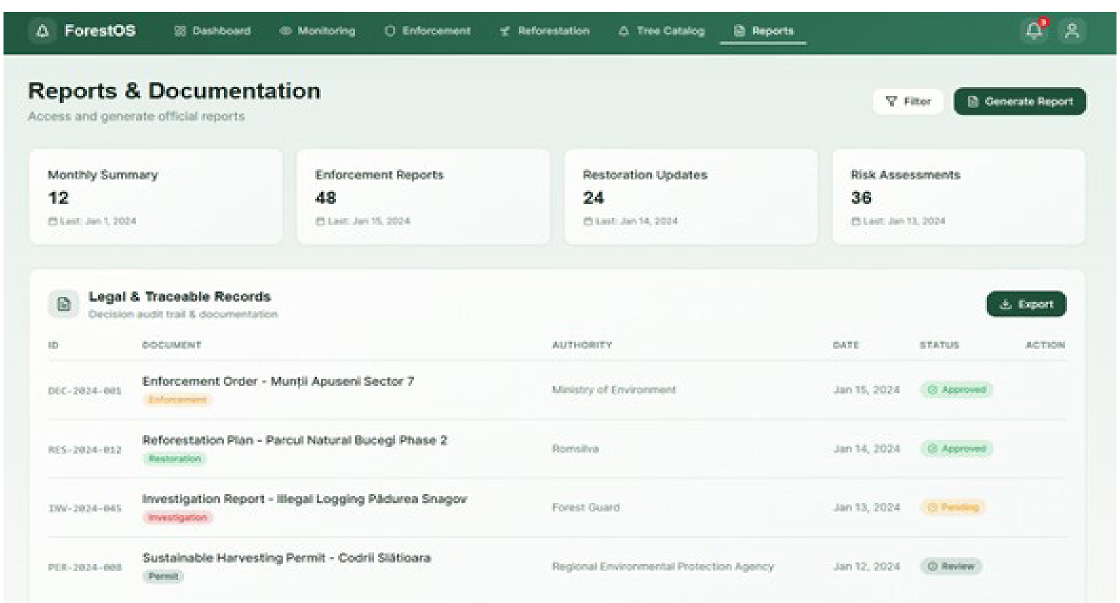

Figure 12. *ForestOS reporting and monitoring dashboard*

The platform maintains a structured registry of legal and operational records, each linked to the one authority that has the issuing obligation of the document type and validation status.

All records are anchored in a cryptographic manner to the permissioned blockchain, enabling independent verification of integrity and provenance while keeping primary data in sovereign off-chain storage. The private blockchain layer is not a technological novelty, but is a fundamental structural component that enables ForestOS to convert the digital observations into legally defensible facts. It underpins trust in digital forest governance and the platform offers it as audit-ready by design.

TAXONOMY AND RESILIENCE IN FORESTOS: A SYNTHESIS AT SYSTEM LAYER

Taxonomy as a governance principle

In the context of ForestOS, taxonomy is the science of classification and systematization of complex domains. Forest governance involves entities such as forest parcels, tree species, assemblages, management regimes, juridical constraints, permits, seeding modalities, institutional roles and evidence types (Buonocore et al., 2022). Without a unifying taxonomic framework, all these elements remain fragmented and difficult to operationalize in an integrated manner.

The ForestOS platform is designed to implement a multilayer taxonomy that organizes a forest domain across several dimensions at a satellite imagery level. Forests are classified into parcels, compartments, protection and restricted categories and functional zones within the forest Digital Twin. At the ecological level, vegetation types, structural attributes, events such as harvesting, transport, afforestation, inspection and drone missions are represented as a standardized case type. At the evidentiary level, satellite products, drone imagery, AI outputs, permits and inspection reports are organized into robust evidence classes with defined provenance and integrity rules.

This taxonomic architecture enables seamless interoperability between the technological layers and the institutional processes. It ensures that satellite-derived change events can be associated without concern with parcels, permits, legal regimes and designated enforcement workflows.

As well, it allows DSS logic, blockchain anchoring and reporting modules to operate on a common semantic foundation. Taxonomy functions as an essential backbone of ForestOS and it transforms heterogeneous data into a coherent knowledge system, enabling automation, explainability and legal defensibility.

Resilience as an emergent property

Resilience is defined as the capacity of an organization or institution to recover rapidly from a state of difficulty and maintain function under stress. In the governance of forests, resilience applies simultaneously to ecosystems and to institutions (Brucherseifer et al., 2025).

ForestOS supports ecological resilience through early detection of disturbances, perpetual monitoring of vegetation health and rapid deployment of restoration interventions, such as precision afforestation. ForestOS increases the probability that forests ecosystem recover before degradation becomes irreversible by shortening the time between disturbance, occurrence and corrective actions.

Institutional resilience is achieved through redundancy, continuity and trust. The DSS provides continuity of operations even under high workload. The private blockchain trust layer ensures that the evidence remains valid and auditable over long time horizons. Even as systems evolve, resilience in ForestOS is an emergent property of the entire architecture.

Taxonomy enables Resilience

Taxonomy and resilience are deeply interdependent within ForestOS. A well-defined taxonomic system- of-systems architecture enables automated reasoning, consistent evidence handling and interoperable workflows. These capabilities create efficient conditions for a resilient operation.

ForestOS has the ability to rapidly reorganize information in response to new threats, policy changes or technological upgrades, due to the classification and systematization of each object, event, or evidence type. New AI models or regulatory requirements can be integrated by extending the existing taxonomies rather than rebuilding the system.

The synthesis explains why ForestOS should be understood as a system-of-systems architecture and not a collection of technologies. The taxonomy provides order while resilience provides endurance and together they allow the platform to operate as a critical digital infrastructure for long-term national forest governance.

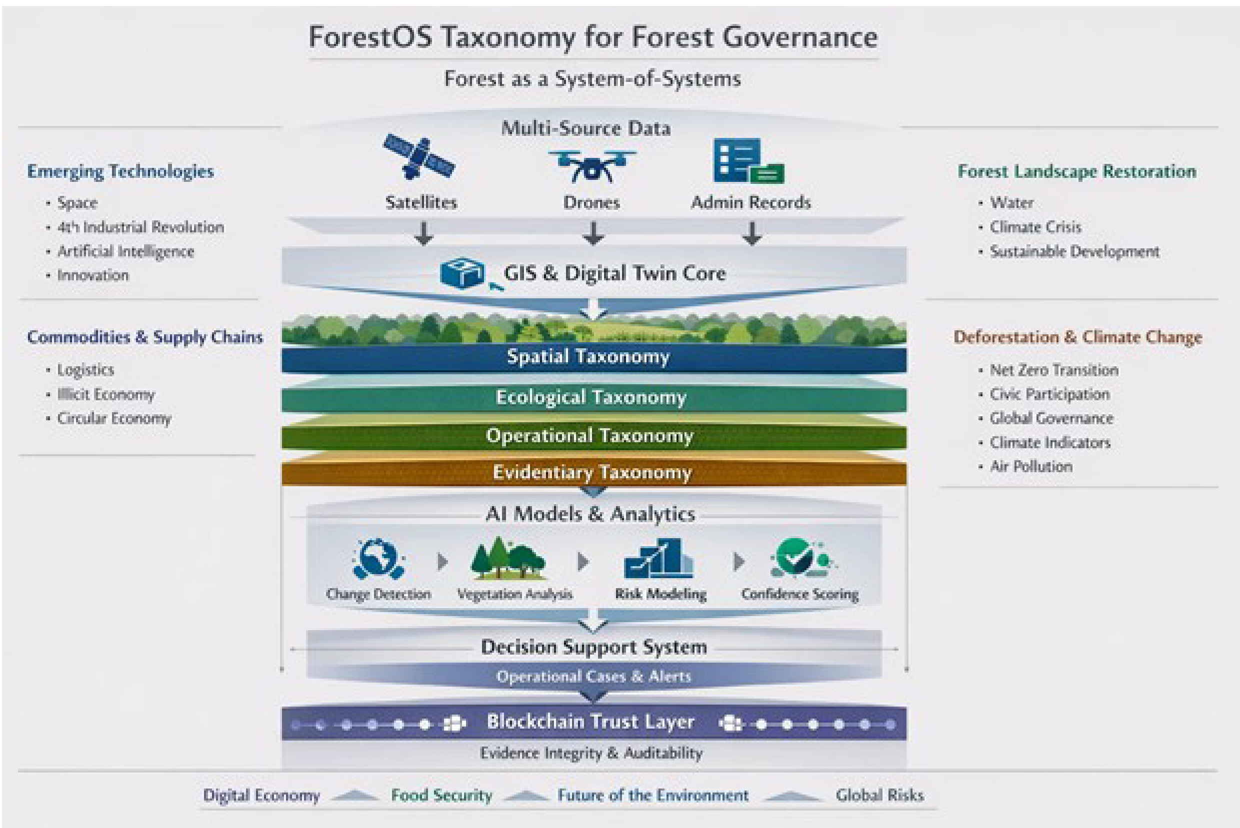

Figure 13. *Forest governance taxonomy as a multi-layer digital ecosystem*

The taxonomic architecture of ForestOS is illustrated in Figure 13 and shows the forest as a central system interconnected with major domains of public policy and impact, including biodiversity, forest communities, landscape restoration, emerging technology, supply chains, forest products and climate pressures.

CONCLUSIONS

ForestOS enables a transition from fragmented oversight and outdated models to a continuous, intelligent and accountable forest governance. It positions Romania as a leader in digital environmental governance and provides a replicable model for other nations

By integrating spatial truth (GIS data as an authoritative substrate) with persistent multi-source observation and cryptographically verifiable evidence, the system treats forests as national critical key assets. This approach enables direct correlation between physical reality on the ground and applicable legal regime, effectively reducing the long-standing gap between detection, intervention and restoration.

The architecture of the ForestOS platform demonstrates that emerging technologies, multispectral satellite imagery, SAR, LiDAR, drones, explainable AI and private blockchain technology can function coherently only when they are embedded within an institutional governance framework.

The AI layer operates not as a positioned autonomous decision maker, but as a probabilistic reasoning engine that can structure risk and enhance institutional capacity for early intervention. Its integration into a human-in-the-loop DSS (Decision Support System) ensures the necessary balance between automation, legal accountability and administrative legitimacy.

Through AI-assisted ecological modeling, versioned prescription, perpetual monitoring of survival rates and cryptographic anchoring of outcomes, ForestOS transforms afforestation and reforestation interventions into measurable and verifiable adaptive processes. The unifying taxonomy of objects, events and evidence types enables interoperability, extensibility and systemic resilience in the face of regulatory change or evolution of technology.

ForestOS provides a replicable "in vitro" model of sovereign digital infrastructure for environmental governance, capable of simultaneously supporting protection, restoration and compliance recording at national and European levels by linking continuous observation to legally defensible, immutable evidence. The system-of-systems architecture provides a transition from declarative policy commitments to performance-based governance grounded in traceable and audit-ready indicators.

ForestOS represents a public institutional architecture for a responsible and transparent stewardship of Romanian capital over the ages to come.

Limitations and Future Research

The present study proposes a conceptual governance architecture and does not claim operational deployment or experimentally validated ecological performance.

Future research directions include pilot implementation within selected Romanian silvic regions, integration with real-time institutional data streams, quantitative benchmarking of AI-assisted detection accuracy and legal validation of blockchain-supported evidentiary workflows.

REFERENCE LIST

5 ways deforestation affects climate change | fsc.org. (n.d.). Retrieved April 22, 2026, from https://fsc.org/en/blog/how-deforestation-affects-climate-change

Abreu-Dias, R., Santos-Gago, J. M., Martín-Rodríguez, F., & Álvarez-Sabucedo, L. M. (2025) Advances in the Automated Identification of Individual Tree Species: A Systematic Review of Drone- and AI-Based Methods in Forest Environments. *Technologies*, 13(5), 187. https://doi.org/10.3390/technologies13050187

Araujo, R., Possebom, V., & Setti, G. (2026) *DETERring more than Deforestation: Environmental Enforcement Reduces Violence in the Amazon*.

Bolcek, J., Gibril, M. B. A., Veverka, J., Sloboda, Š., Maršálek, R., & Götthans, T. (2025) Spaceborne LiDAR Systems: Evolution, Capabilities, and Challenges. *Sensors,* 25(12), 3696. doi: 10.3390/s25123696

Brancalion, P. H. S., & Holl, K. D. (2020). Guidance for successful tree planting initiatives. *Journal of Applied Ecology*, 57(12), 2349–2361. doi: 10.1111/1365-2664.13725

Brucherseifer, E., Marquard, M., Hellmann, M., & Tundis, A. (2025) *Data Taxonomy Towards the Applicability of the Digital Twin Conceptual Framework in Disaster Management*. https://arxiv.org/pdf/2503.00076

Buchelt, A., Adrowitzer, A., Kieseberg, P., Gollob, C., Nothdurft, A., Eresheim, S., Tschiatschek, S., Stampfer, K., & Holzinger, A. (2024) Exploring artificial intelligence for applications of drones in forest ecology and management. *Forest Ecology and Management*, 551, 121530. doi: 10.1016/j.foreco.2023.121530

Buonocore, L., Yates, J., & Valentini, R. (2022). A Proposal for a Forest Digital Twin Framework and Its Perspectives. *Forests*, 13(4), 498. doi: 10.3390/f13040498

Canisius, F., Brisco, B., Murnaghan, K., Van Der Kooij, M., & Keizer, E. (2019). SAR Backscatter and InSAR Coherence for Monitoring Wetland Extent, Flood Pulse and Vegetation: A Study of the Amazon Lowland. *Remote Sensing,* 11(6), 720. doi: 10.3390/rs11060720

Copernicus Land Monitoring Service. (n.d.). Retrieved May 12, 2026, from https://land.copernicus.eu/en

Corporate Implementation, Impacts and Reporting on No-Deforestation & "Nature Positive" Post 2020 - Forest Trends. (n.d.). Retrieved April 22, 2026, from https://www.forest-trends.org/publications/corporate-implementation-impacts-and-reporting/

Crouzeilles, R., Curran, M., Ferreira, M. S., Lindenmayer, D. B., Grelle, C. E. V., & Rey Benayas, J. M. (2016) A global meta-analysis on the ecological drivers of forest restoration success. *Nature Communications,* 7(1), 11666. doi:10.1038/ncomms11666

Deforestation in Europe: Where it's happening and how to combat it | fsc.org. (n.d.) Retrieved April 22, 2026, from https://fsc.org/en/blog/deforestation-in-europe

Earth Engine Data Catalog | Google for Developers. (n.d.) Retrieved April 22, 2026, from https://developers.google.com/earth-engine/datasets/catalog

Forest assessment and monitoring | FAO | Food and Agriculture Organization of the United Nations. (n.d.). Retrieved April 22, 2026, from https://www.fao.org/forestry/our-focus/assessment-monitoring/en

Forest monitoring - Environment - European Commission. (n.d.) Retrieved April 22, 2026, from https://environment.ec.europa.eu/topics/forests/forest-monitoring_en?

Forest Monitoring, Land Use & Deforestation Trends | Global Forest Watch. (n.d.) Retrieved May 12, 2026, from https://www.globalforestwatch.org/

Home | Convention on Biological Diversity. (n.d.). Retrieved April 22, 2026, from https://www.cbd.int/

How Drones and AI Are Making Forests More Valuable | Riga Technical University. (n.d.). Https://Www.Rtu.Lv. Retrieved April 22, 2026, from https://www.rtu.lv/en/university/for-mass-media/news/open/how-drones-and-ai-are-making-forests-more-valuable

How the FSC System Works | Forest Stewardship Council. (n.d.) Retrieved April 22, 2026, from https://fsc.org/en/how-the-fsc-system-works

International Illegal Logging: Background and Issues | Congress.gov | Library of Congress. (n.d.) Retrieved April 22, 2026, from https://www.congress.gov/crs-product/IF11114

Investigations and Inspections. (n.d.) Retrieved April 22, 2026, from https://www.esma.europa.eu/esmas-activities/supervision/investigations-and-inspections

Korbik, M., Swoczyna, T., & Latocha, P. (2025) Pre-Planting and Planting Factors and Practices Affecting Urban Tree Growth: With a Special Focus on the Root System and Its Condition—A Review. *Plants*, 14(3), 387. doi: org/10.3390/plants14030387

Kovačovič, P., Pirník, R., Kafková, J., Michálik, M., Kanáliková, A., & Kuchár, P. (2025) Satellite-Based Forest Stand Detection Using Artificial Intelligence. *IEEE Access*, 13, 10898–10917. doi:10.1109/ACCESS.2025.3528215

Kundu, S., Ninoria, S. Z., Chaturvedi, R. P., Mishra, A., Agrawal, A., Batra, R., Dubale, M., & Hashmi, A. (2025) Real-time deforestation anomaly detection using YOLO and LangChain agents for sustainable environmental monitoring. *Scientific Reports*, 15(1), 39961. https://doi.org/10.1038/s41598-025-23617-4

Liang, X., Yu, S., Meng, B., Wang, X., Yang, C., Shi, C., & Ding, J. (2025) Multi-Source Remote Sensing and GIS for Forest Carbon Monitoring Toward Carbon Neutrality. *Forests*, 16(6), 971. doi:10.3390/f16060971

Misra, G., Cawkwell, F., & Wingler, A. (2020) Status of Phenological Research Using Sentinel-2 Data: A Review. *Remote Sensing*, 12(17), 2760. doi: 10.3390/rs12172760

New York Declaration on Forests - Forest Declaration Assessment. (n.d.). Retrieved April 22, 2026, from https://forestdeclaration.org/about/new-york-declaration-on-forests

Păduri | WWF Romania. (n.d.) Retrieved April 22, 2026, from https://wwf.ro/ce-facem/paduri/

Precision Forestry - Geospatial Forestry Platform - Swift Geospatial. (n.d.). Retrieved May 12, 2026, from https://forestryplatform.com/

Restoration Reports. (n.d.) Retrieved April 22, 2026, from https://grih.info/restoration-reports/

Roberts, J. F., Mwangi, R., Mukabi, F., Njui, J., Nzioka, K., Ndambiri, J. K., Bispo, P. C., Espirito-Santo, F. D. B., Gou, Y., Johnson, S. C. M., Louis, V., Pacheco-Pascagaza, A. M., Rodriguez-Veiga, P., Tansey, K., Upton, C., Robb, C., & Balzter, H. (2022) Pyeo: A Python package for near-real-time forest cover change detection from Earth observation using machine learning. *Computers & Geosciences*, 167, 105192. doi: 10.1016/j.cageo.2022.105192

Seddon, N., Smith, A., Smith, P., Key, I., Chausson, A., Girardin, C., House, J., Srivastava, S., & Turner, B. (2021) Getting the message right on nature-based solutions to climate change. *Global Change Biology*, 27(8), 1518–1546. doi: 10.1111/gcb.15513

State of Europe's Forests 2025 Report (SoEF 2025) - FOREST EUROPE. (n.d.) Retrieved April 22, 2026, from https://foresteurope.org/publications_type/soef-2025/

Strategic Intelligence. (n.d.) Retrieved April 22, 2026, from https://intelligence.weforum.org/topics/a1Gb00000015HiiEAE

Such, K., Biggie, H., & Heckman, C. (2023). Restorebot: Towards an Autonomous Robotics Platform for Degraded Rangeland Restoration.

THE 17 GOALS | Sustainable Development. (n.d.). Retrieved April 22, 2026, from https://sdgs.un.org/goals

The Bonn Challenge | Bonchallenge. (n.d.) Retrieved April 22, 2026, from https://www.bonnchallenge.org/

The European Green Deal - European Commission. (n.d.) Retrieved April 22, 2026, from https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

Torres, P., Rodes-Blanco, M., Viana-Soto, A., Nieto, H., & García, M. (2021) The Role of Remote Sensing for the Assessment and Monitoring of Forest Health: A Systematic Evidence Synthesis. *Forests*, 12(8), 1134. doi: 10.3390/f12081134

Ultimele păduri seculare din Europa, mai bine protejate | WWF. (n.d.). Retrieved April 22, 2026, from https://wwf.panda.org/es/?200433/Ultimele-pduri-seculare-din-Europa-mai-bine-protejate