

MODELING A FOREST INVENTORY PROTOCOL WITH HSI AND LIDAR FOR REDD+ PROJECTS: AN INTEGRATED APPROACH WITH BLOCKCHAIN

**MODELAGEM DE UM PROTOCOLO DE INVENTÁRIO FLORESTAL COM HSI E
LIDAR PARA PROJETOS REDD+: UMA ABORDAGEM INTEGRADA COM
BLOCKCHAIN**

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ABSTRACT

This article presents the design of a forest inventory protocol aimed at REDD+ projects in Brazil, integrating advanced remote sensing technologies such as hyperspectral sensors (HSI), LiDAR, and immutable record-keeping systems via blockchain. The proposal is based on a comparative analysis of the methodological standards of the Verified Carbon Standard (Verra) and the Gold Standard, assessing their compatibility using geospatial data and carbon indicators. The adopted methodology includes document review, identification of operational gaps, and the development of a modular technical workflow with steps for stratification, sampling, biomass modeling, validation, and digital auditing. The protocol complies with Brazilian regulations (CONAREDD+, National Forest Inventory, ISO 14064) and can be implemented in community-based, jurisdictional, or hybrid projects. Expected outcomes include greater accuracy in carbon estimation, reduced fieldwork costs, and enhanced transparency in verification processes. The integration between digital technologies and national regulatory frameworks represents a methodological advance for nature-based initiatives, with the potential to strengthen climate integrity and the socio-environmental benefits of projects.

Keywords: REDD+; Inventory; Remote Sensing; LiDAR; Blockchain; Brazil.

RESUMO

Este artigo apresenta o projeto de um protocolo de inventário florestal voltado para projetos REDD+ no Brasil, integrando tecnologias avançadas de sensoriamento remoto, como sensores hiperespectrais (HSI), LiDAR e sistemas imutáveis de registro de dados via blockchain. A proposta baseia-se em uma análise comparativa dos padrões metodológicos do Verified Carbon

Standard (Verra) e do Gold Standard, avaliando sua compatibilidade por meio de dados geoespaciais e indicadores de carbono. A metodologia adotada inclui revisão documental, identificação de lacunas operacionais e o desenvolvimento de um fluxo de trabalho técnico modular com etapas para estratificação, amostragem, modelagem de biomassa, validação e auditoria digital. O protocolo está em conformidade com as regulamentações brasileiras (CONAREDD+, Inventário Florestal Nacional, ISO 14064) e pode ser implementado em projetos comunitários, jurisdicionais ou híbridos. Os resultados esperados incluem maior precisão na estimativa de carbono, redução dos custos de trabalho de campo e maior transparência nos processos de verificação. A integração entre tecnologias digitais e marcos regulatórios nacionais representa um avanço metodológico para iniciativas baseadas na natureza, com potencial para fortalecer a integridade climática e os benefícios socioambientais dos projetos.

Palavras-chave: REDD+; Inventário; Sensoriamento Remoto; LiDAR; Blockchain; Brasil.

INTRODUCTION

Given the intensification of the global climate crisis, the urgency for effective strategies to mitigate greenhouse gas (GHG) emissions has increased. In this context, REDD+ projects (Reducing Emissions from Deforestation and Forest Degradation) have emerged as a promising response, owing to their unique capacity to integrate forest conservation, socio-economic inclusion, and innovative climate finance mechanisms. Recently, the incorporation of digital technologies, such as blockchain-based distributed ledger systems, has consolidated as a viable alternative to strengthen transparency

and governance in environmental protection initiatives (Angelsen et al., 2018).

The scientific robustness and institutional acceptance of REDD+-based initiatives are directly linked to the accuracy and consistency of forest inventories used in the quantification and monitoring of carbon stocks (West et al., 2020). As the demand for verifiable and accessible systems grows particularly in contexts involving a diversity of stakeholders and interests innovative technologies such as hyperspectral sensors (HSI), LiDAR platforms, and decentralized digital records are emerging as promising tools to strengthen the reliability of Monitoring, Reporting, and Verification (MRV) processes (Reyna et al., 2018).

Figure 1, illustrates the sequential integration of innovative technologies in REDD+ projects, highlighting the transition from inconsistent forest inventories to reliable carbon stock monitoring. The process involves the adoption of hyperspectral sensors to enhance forest data acquisition, LiDAR platforms for accurate 3D structural mapping, and decentralized digital records to ensure transparent and verifiable data storage, culminating in reliable MRV results.

Figure 1. Enhancing REDD+ with Innovative Technologies.

Aprimorando o REDD+ com Tecnologias Inovadoras



Made with Napkin

Source: Prepared by the authors.

Although they present consolidated and technically structured methodologies, the inventory protocols adopted by certification standards such as Verra (Verified Carbon Standard – VCS) and the Gold Standard still make limited use of the resources offered by high-resolution remote sensing technologies. Additionally, the absence of formal mechanisms for integrating decentralized record systems, such as blockchain technology, restricts advances in the verifiability and digital traceability of the generated data flows (Simonet et al., 2015).

The advancement and increased accessibility of hyperspectral sensors (HSI) and LiDAR (Light Detection and Ranging) systems have significantly expanded the potential for structural and biophysical analysis of forest formations, especially in remote or hard-to-monitor areas. Recent scientific evidence indicates that the synergistic combination of these technologies enhances the accuracy of aboveground biomass and carbon estimates while reducing uncertainties associated with conventional allometric models (Asner et al., 2012). Furthermore, this approach facilitates

integration with georeferenced data, automated MRV tools, and blockchain-based digital solutions, optimizing the environmental monitoring cycle.

In this context, the present study proposes an integrated methodological framework for forest inventory in REDD+ projects, incorporating hyperspectral sensors (HSI), LiDAR technology, and digital authentication mechanisms via blockchain. The model aims to ensure the traceability, immutability, and verifiability of information flows, thereby contributing to greater technical legitimacy in measurement processes. Based on a comparative analysis between the Verra and Gold Standard frameworks, it outlines an operational arrangement aimed at reducing information asymmetries, strengthening trust among the stakeholders involved, and generating highly reliable carbon credits (Casino, Dasaklis, & Patsakis, 2019).

The adoption of decentralized digital infrastructures, such as blockchain technology, has been consolidated as a strategic alternative to strengthen the integrity and reliability of multisectoral environmental systems. In initiatives involving governments, local communities, and private stakeholders, its application enables the immutable authentication of monitoring data, reduces vulnerability to undue manipulation, and enhances the informational resilience of voluntary carbon markets (Casino, Dasaklis, & Patsakis, 2019).

Comparative Framework: Gold Standard and Verra (VCS)

The two main international frameworks for carbon credit certification in REDD+ projects the Verified Carbon Standard (VCS) by Verra and the Gold Standard, employ methodologies with varying

levels of technical detail and operational requirements for conducting forest inventories. This methodological divergence creates a gap, enabling the development of models and the adoption of new geospatial technologies, such as hyperspectral sensors (HSI), LiDAR, and decentralized digital registry infrastructures, thereby significantly enhancing the scalability, adaptability, and visibility of Monitoring, Reporting, and Verification (MRV) processes (FAO, 2021).

The VCS standard, maintained by Verra, is characterized by strictly quantitative methodologies with detailed validation and verification requirements. In contrast, the Gold Standard adopts a more modular approach, focused on valuing socio-environmental co-benefits and explicitly aligning with the Sustainable Development Goals (SDGs).

Understanding these distinctions is essential for developing methodological protocols that reconcile technical rigor with applicability across diverse territorial contexts. Digital solutions such as blockchain can contribute in this regard by strengthening information security, field traceability, and the reliability of interactions between local communities and certification systems (Gebara et al., 2020).

The Verified Carbon Standard (VCS), developed by Verra, adopts a robust and highly prescriptive methodological approach, with specific tools aimed at carbon quantification in different forest contexts. An example is the VM0048 methodology, widely used in avoided deforestation initiatives in tropical areas. These protocols require detailed spatial modeling in the definition of baselines, the use of georeferenced historical series, and integration with high-

resolution remote sensing systems, including orbital imagery and detailed thematic stratification.

However, although formally prescribed, this spatial modeling often relies on generic parameters such as anthropic pressure, accessibility, and land use, and is not always able to adequately represent the ecological and socio-territorial complexity of Brazil. This limitation becomes even more critical in regions such as the Amazon, where landscape diversity, gaps in land tenure data, and traditional patterns of land occupation pose challenges to the direct application of standardized models.

Such methodological constraints reinforce the need for territory-sensitive adaptations and highlight the complementary role of digital solutions, such as blockchain technology, in ensuring auditability and traceability in environments with high operational complexity. Verra itself supports this view (Verra, 2021).

Within the scope of the Land Use & Forests (LUF) program, the Gold Standard structures its methodologies in a modular and adaptable manner, prioritizing alignment with the Sustainable Development Goals (SDGs) and the enhancement of socio-environmental co-benefits. Tools such as the “Trees for All” guides and specific methodologies for agroforestry and reforestation support the incorporation of local realities, making this standard particularly well-suited for community-based, territorial, and socially focused initiatives.

However, authors such as Kowler et al. (2020) and Gebara et al. (2020) point out that this flexibility may require greater local technical rigor to ensure consistency, auditability, and comparability

among projects. In these contexts, the application of digital technologies, such as blockchain, can enhance the visibility and trust in processes by enabling participatory audits, decentralized traceability, and transparent recording of actions carried out by the communities involved.

In contrast to the VCS, the Gold Standard establishes mandatory alignment with the United Nations Sustainable Development Goals (SDGs) as a core criterion, placing emphasis on social, economic, and environmental co-benefits rather than on rigid technical requirements for carbon quantification. This approach has fostered the inclusion of projects led by community organizations and grassroots initiatives, promoting positive impacts at the local scale.

However, as noted by Gebara et al. (2020), this flexibility can hinder the standardization of metrics and compromise comparability among projects, particularly regarding the measurement of non-monetary benefits. Technologies such as hyperspectral sensors (HSI) and LiDAR, combined with blockchain-based digital records, offer promising pathways to support the measurement of indicators associated with the SDGs, such as land cover, vegetation dynamics, and ecological integrity, with greater precision and auditability (Asner et al., 2012; Gold Standard, 2023).

Understanding the conceptual and operational differences between the Verra and Gold Standard frameworks is crucial for developing forest inventory protocols that reconcile technical rigor with socio-territorial relevance. The methodological proposal presented here seeks precisely to bridge these approaches, combining the normative robustness of the VCS with the community-oriented adaptability promoted by the Gold Standard.

The integration of hyperspectral sensors (HSI), capable of detecting biochemical variations in vegetation, and LiDAR technology, aimed at three-dimensional structural characterization of forests, enables the generation of high-resolution data applicable to biomass estimation and the validation of environmental co-benefits. When combined with blockchain-based digital record systems, these resources provide auditable traceability and multisectoral transparency. Such convergence is strategic for strengthening trust among diverse actors, including technical, institutional, and community stakeholders, while also democratizing access to nature-based climate compensation mechanisms (Kollert & Lambert, 2020; Gebara et al., 2020).

Regarding baseline construction, both standards require the definition of a reference scenario that justifies the avoided emissions. Verra sets out detailed guidelines based on rigorous spatial modeling and consolidated historical series, while the Gold Standard allows for more simplified solutions, particularly in community contexts and in situations with lower institutional capacity.

This flexibility broadens methodological access but may compromise the accuracy of estimates if not accompanied by consistent technical justifications and a minimum infrastructure for data collection and validation. In such cases, the use of digital verification mechanisms, such as auditable and chronologically traceable records, can support methodological integrity even in less structured protocols (FAO, 2019).

The technical support tools offered by certification standards present significant differences in their level of methodological structuring and automation. Verra provides resources such as the

Stratification Tool, specific modules for baseline construction, emission factor libraries, and utilities for automated vegetation stratification using remote sensing, elements that can facilitate process standardization in certain contexts.

In contrast, the Gold Standard offers more flexible and decentralized support, placing greater responsibility on the proponent for the formulation and technical justification of the methods adopted. This approach allows for greater local adaptation but may pose a barrier to the incorporation of more sophisticated geospatial technologies, such as HSI and LiDAR, especially when technical or institutional limitations exist. The proposal presented here seeks precisely to integrate the most structured aspects of both models, reconciling replicability with territorial adaptability (Verra, 2022; Gold Standard, 2023).

Another relevant point of distinction between the standards is the treatment of uncertainty associated with carbon estimates. Verra requires projects to quantify, report, and incorporate uncertainty margins into the final calculations, using robust statistical methods and, in some cases, applying penalties to the credits generated when uncertainty exceeds certain limits.

The Gold Standard, on the other hand, adopts a more qualitative or modular approach, depending on the methodology applied, which may limit comparability between projects and the reliability of data for more demanding markets. In such cases, the integration of technologies such as HSI and LiDAR represents a concrete opportunity to reduce sampling variability and increase accuracy (IPCC, 2019).

Finally, although both standards require independent audits to verify results, the Gold Standard distinguishes itself by explicitly incorporating the validation of impacts on the Sustainable Development Goals (SDGs). This requirement broadens the scope for applying remote sensing technologies, such as HSI and LiDAR, which can be used not only for biomass estimation but also for measuring indicators related to vegetation cover, land use change, and environmental integrity.

Despite their potential, these technologies are still underutilized in a systematic manner for multisectoral monitoring and co-benefit validation, especially in community-based projects (Gebara et al., 2020; Kowler et al., 2020). The protocol proposed here seeks precisely to operationalize this use, providing an integrated and auditable framework to generate technical and scientific evidence compatible with the SDGs. Additionally, the application of blockchain strengthens the traceability and public accessibility of this evidence, contributing to the social and climate transparency of verification processes (Gold Standard, 2023).

Objective of the Article

To propose a technical forest inventory protocol model integrating hyperspectral sensors (HSI), LiDAR technology, and blockchain records, tailored to REDD+ projects, grounded in the methodological requirements of the Verra (VCS) and Gold Standard frameworks, with the goals of transparency, traceability, accuracy, and applicability in tropical contexts.

Specific Objectives

- To evaluate the forest inventory methodologies, present in the Verra (VM0048) and Gold Standard frameworks.
- To identify the technical and operational limitations of using HSI and LiDAR in MRV protocols applied to REDD+.
- To propose an adapted methodological framework integrating HSI, LiDAR, and blockchain.
- To demonstrate the compatibility of the proposal with Brazilian legislation and technical standards (CONAREDD+, IFN, ISO).
- To suggest guidelines for the technical validation and adoption of the protocol by jurisdictional and community-based projects.

TECHNICAL PROTOCOL PROPOSAL WITH HSI, LIDAR, AND BLOCKCHAIN

Technical Justification

The development of a technical forest inventory protocol for REDD+ projects requires the articulation of scientific accuracy, operational feasibility, and compliance with certification standard requirements. Traditional field sampling approaches, although well-established, present significant limitations in terms of spatial coverage, cost, time, and replicability, particularly in complex and remote tropical ecosystems. Emerging technologies such as hyperspectral sensors (HSI), LiDAR, and blockchain offer complementary and innovative solutions to address these limitations.

This section presents the detailed proposal of a technical protocol that seeks to integrate these technologies into an adaptable and

scalable operational model aligned with international (Verra, Gold Standard) and national (CONAREDD+, IFN) standards. The proposal aims not only to enhance the technical rigor of biomass and carbon estimates but also to incorporate mechanisms for digital traceability, auditability, and trust among multiple stakeholders, requirements increasingly demanded by carbon markets and climate finance providers.

Proposed Protocol Stages

The proposed protocol follows a logical and technical sequence that ensures compatibility with the main international methodological standards. The stages are:

Delimitation of the Area and Sampling Design

Geospatial delimitation and sampling design form the operational foundation of the protocol, ensuring that the entire measurement and verification chain is consistent with technical and legal standards. This stage comprises the following subcomponents:

- a. Use of satellite imagery for the initial delimitation of the project area. The project area must be defined using updated multispectral satellite imagery (e.g., Sentinel-2, PlanetScope) integrated with official vector data such as CAR, INCRA, or Indigenous territory boundaries. This initial delimitation must comply with the eligibility criteria of the adopted standard (Verra or Gold Standard), ensuring continuous forest cover, no overlap with excluded areas, and additional carbon potential.
- b. Definition of representative sample plots based on prior environmental stratification. Sampling delimitation follows a

multivariate environmental stratification based on geospatial data such as land use, phytophysiology, topography, and deforestation history. This stratification can be performed using unsupervised algorithms (e.g., k-means) or specialized tools such as the Stratification Tool (Verra). From the homogeneous strata generated, the arrangement of sample plots is defined using a stratified random design, ensuring statistical robustness and spatial representativeness, as well as providing direct support for the calibration of HSI and LiDAR data in subsequent stages (IPCC, 2019).

Figure 2 – Process of Area Delimitation and Sampling



Source: Prepared by the authors.

Remote Data Acquisition

The integrated acquisition of HSI and LiDAR data forms the technical core of the protocol, enabling spectral, structural, and biophysical characterization of the forest with high resolution and replicability. This stage is divided into two main subitems, according to the platforms used for obtaining the spectral data.

a. Collection of hyperspectral (HSI) imagery via satellite and drone Hyperspectral imagery must be acquired through two complementary platforms:

- Hyperspectral satellites (e.g., PRISMA, EnMAP, or future platforms such as CHIME), which provide regional coverage and temporal continuity for monitoring.
- Drones equipped with HSI cameras, which offer ultra-high spatial resolution (<1 m) and spectral resolution (<10 nm), suitable for plot calibration and species analysis.

The data must cover the visible (VIS), near-infrared (NIR), and shortwave infrared (SWIR) ranges, with radiometric control and atmospheric correction applied. The choice of platform will depend on the project scale and budget conditions, and they may be combined through spectral fusion.

b. Structural scanning with airborne LiDAR

Airborne LiDAR must operate with multi-return sensors, a minimum point density of 10 pts/m², and preferably with full waveform capability. Flights must be georeferenced using differential GPS support (RTK or PPK) and conducted under optimal weather conditions.

LiDAR data will enable the generation of derivative products such as:

- Digital Surface Model (DSM)
- Digital Terrain Model (DTM)

- Canopy Height Model (CHM)
- Vertical vegetation profile

Integration with HSI data takes place in a GIS environment, where spectral and structural layers are overlaid for multivariate analysis and subsequent modeling stages.

Data Preprocessing and Calibration

The preprocessing and calibration stage ensures the quality, comparability, and integrity of the data acquired by remote sensors, being essential to transform raw data into useful information for the forest inventory. This stage involves technical processes for correction, integration, and cross-validation with field data.

a. Spectral and structural preprocessing

HSI data must undergo radiometric correction, atmospheric correction (using models such as FLAASH or ATCOR), removal of noisy bands (e.g., water vapor absorption), and dimensionality reduction through methods such as Principal Component Analysis (PCA). LiDAR data, in turn, are processed to generate a classified point cloud (ground vs. vegetation), altitude normalization, and extraction of structural metrics (mean height, maximum height, layer density).

b. Multisensor and geospatial integration

After spectral and structural standardization, the data are integrated in a GIS environment through georeferenced overlay (pixel-by-pixel or by plot). This integration is essential for enabling multivariate

analyses and the fusion of spectral structural data, supporting subsequent stages of stratification and modeling.

c. Calibration with field data and allometric models

The processed data are calibrated with georeferenced field plots (preferably from the National Forest Inventory or local inventories), using variables such as diameter at breast height (DBH), total height, and basic wood density. Calibration is performed using multivariate regressions, Random Forest, or neural networks, depending on the data volume. Regional allometric models are adjusted based on the metrics derived from the sensors to estimate aboveground biomass and carbon (Chaves, 2014).

Biomass and Carbon Stock Modeling

The modeling stage aims to transform the calibrated spectral and structural data into quantitative estimates of aboveground biomass and carbon, in accordance with the requirements of REDD+ standards such as Verra and the Gold Standard. The accuracy of this modeling is critical to ensuring transparency, replicability, and confidence in the carbon credits generated.

a. Generation of composite predictor variables (HSI + LiDAR)

Spectral variables (vegetation indices, principal components) and structural variables (mean height, canopy density, vertical roughness) are selected and combined into multivariate predictor matrices. This approach makes it possible to simultaneously capture the biochemical and structural characteristics of vegetation.

b. Statistical modeling and machine learning

Multivariate regression models, Random Forest, Support Vector Machines (SVM), and artificial neural networks are applied to estimate biomass per pixel or per plot, using the calibrated data from the previous stage. Model selection is based on criteria such as R^2 , RMSE, and cross-validation (k-fold).

c. Conversion to carbon and application of emission factors

The estimated biomass is converted to carbon using regional factors (e.g., 0.47 for dry biomass), in accordance with IPCC guidelines. The corresponding emission factor (CO_2e) is then applied based on the project methodology (e.g., VM0048), enabling the calculation of the total avoided or captured emissions.

Technical Reports and Products for MRV

The final stage of the technical chain is responsible for documenting and systematizing the results obtained throughout the protocol, in order to meet the requirements of MRV (Measurement, Reporting, and Verification) systems established by standards such as Verra and the Gold Standard. The transparency, consistency, and auditability of the products generated are essential for the eligibility and certification of carbon credits (Verra, 2023).

a. Preparation of technical reports

Documents are compiled containing a detailed description of the methodologies applied, parameters used, data sources, adjusted models, and accuracy metrics. These reports must follow the guidelines of the certification standards, such as the VCS or Gold Standard templates, and include thematic maps, scatter plots, and statistical results tables.

b. Generation of auditable geospatial products

The main georeferenced products include:

- Biomass and carbon maps by stratum or by pixel.
- Uncertainty and standard error maps.
- Standardized Shapefiles and GeoTIFFs for submission to carbon registries.
- Metadata compliant with ISO 19115 standards.

c. Linking with verification systems and blockchain

All reports and geospatial files receive unique identifiers (hashes) and are recorded in a compatible blockchain system, ensuring traceability and integrity. These records can be accessed by independent auditors and integrated into the platforms of international standards.

Validation and Uncertainty Calculation

The assessment of uncertainty associated with biomass and carbon estimates is an essential requirement in REDD+ certification standards, such as Verra (VM0048) and IPCC guidelines. This stage ensures the scientific credibility of the inventory and directly affects the number of eligible credits.

a. Statistical validation of estimates

Cross-validation techniques (e.g., k-fold), correlation between estimated plots and field measurements, and the evaluation of metrics such as root mean square error (RMSE), coefficient of determination (R^2), and bias are applied. These analyses make it possible to quantify the degree of fit of predictive models and identify potential methodological adjustments.

b. Calculation of total uncertainty and error propagation analysis

Total uncertainty is estimated using error propagation methods involving the sensing components (HSI and LiDAR), sampling, modeling, and biomass-to-carbon conversion. The recommended approach follows the combined uncertainty formula and, when possible, employs Monte Carlo simulations to test the stability of the results.

c. Application of adjustment factors according to the adopted standard

In accordance with the VM0048 methodology, when uncertainty exceeds the established limit (e.g., 15%), a discount factor is applied to the credits generated. In the case of more flexible methodologies, such as the Gold Standard, the uncertainty must be reported and technically justified (Awuah, 2016).

Recording, Traceability, and Auditing via Blockchain

Traceability and transparency of the information generated in the forest inventory are essential components for ensuring climate integrity, building trust among stakeholders, and enabling the auditability of carbon credits. The integration of blockchain technology into the proposed protocol allows for the immutable and

decentralized recording of the main stages of the MRV process, in addition to enabling the use of smart contracts linked to technical and social verifications.

a. Generation of cryptographic identifiers (hashes)

Each technical product generated, such as processed HSI and LiDAR images, statistical models, technical reports, and metadata files must receive a unique identifier based on SHA-256 or similar hashing. These hashes act as digital seals that ensure data integrity over time, enabling cross-verification between versions and protection against unauthorized manipulation.

b. Immutable blockchain recording

The critical identifiers and metadata for each stage are recorded on a public blockchain (e.g., Ethereum, Polygon) or a private blockchain (e.g., Hyperledger), with a timestamp, geocode of the project area, and the public key of the technical lead. This structure ensures continuous traceability and auditability, with public and transparent access to the information. According to Reyna et al. (2018), blockchain technology offers a reliable solution for multisectoral environmental systems, especially when multiple verifiers and complex validation processes are involved.

c. Integration with the MRV cycle and smart contracts

The Monitoring, Reporting, and Verification (MRV) stages are linked through blockchain logic, allowing each independent verification to generate a new block connected to the previous one. Smart contracts can be used to automatically release carbon credits after

technical validation and external auditing, promoting efficiency, trust, and automation in results-based payment processes.

d. Public query interface and reproducibility

A web dashboard (Web3) can be developed to provide public access to the history of technical deliverables recorded on the blockchain, enabling local communities, auditors, financiers, and regulatory agencies to consult the data. This strengthens the principle of transparency and ensures social oversight of REDD+ projects.

e. Structure of the implemented blockchain model

The protocol proposes the use of a blockchain-based architecture compatible with public networks (e.g., Polygon, Ethereum) or private networks (e.g., Hyperledger), with a modular structure for tracking, verification, and querying. Each technical stage of the MRV (Measurement, Reporting, and Verification) process is encoded into three hash layers:

- Primary hash (H1): linked to the raw technical product (e.g., LiDAR point cloud, HSI spectral cube).
- Secondary hash (H2): associated with the corresponding technical report.
- Verification hash (H3): resulting from the concatenation of H1 and H2, stored on the blockchain with a timestamp and public key.

The encryption algorithm used follows the SHA-256 standard, ensuring data security and integrity. The records are structured in

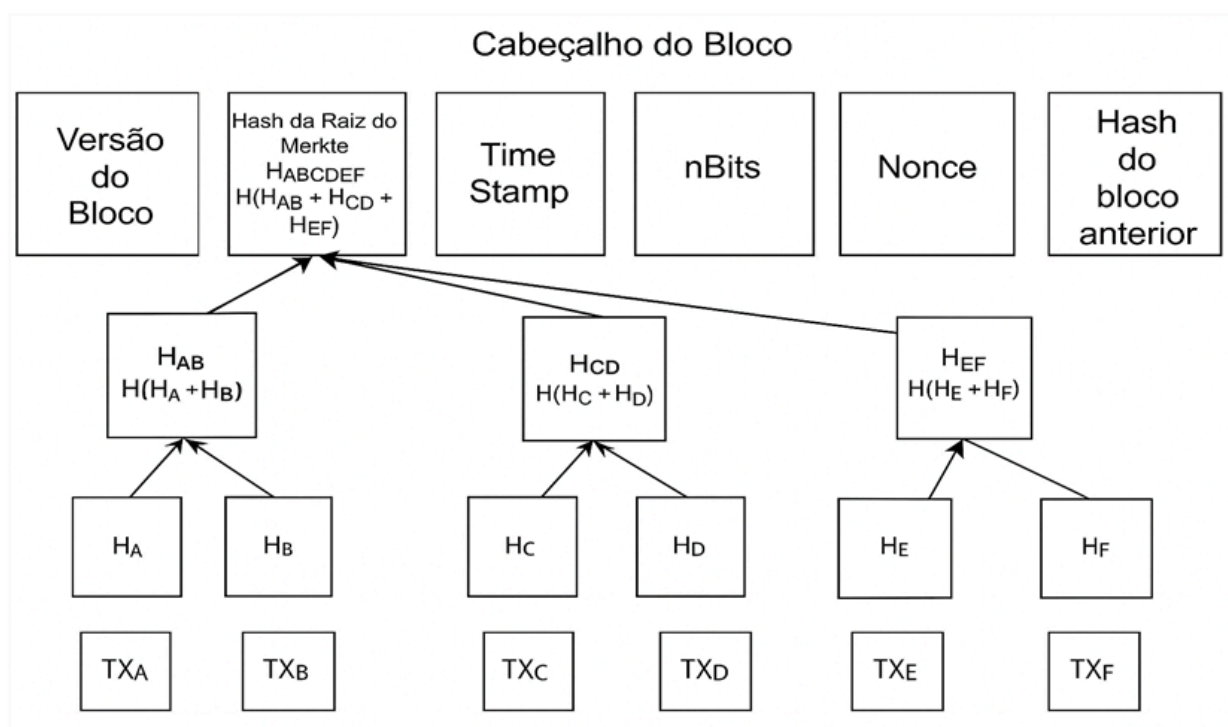
smart contracts that enable automatic triggers for credit release after technical and social verification. This architecture is compatible with Web3 dashboards and can be integrated into national and international registry and verification systems.

The source code structure is developed in Solidity (for EVM-based networks), with open documentation and version control in a Git repository (private or public), allowing independent auditing and reproducibility. The modularity of the system enables replication in different projects and biomes, as well as customization by regional technical agents.

To better understand the blockchain architecture described, a schematic of a block with its corresponding Merkle tree is presented below. This structure illustrates how the cryptographic identifiers (hashes) H1, H2, and H3 are organized and linked to the technical transactions of the MRV protocol, ensuring integrity, immutability, and verifiability at each stage of the process.

Figure 4 presents the blockchain block structure, which encodes the technical products into different hash layers through the Merkle tree. This architecture ensures cryptographic traceability and integrates the records into smart contracts for automated MRV.

Figure 3. Structure of a block with a Merkle tree applied to the REDD+ protocol



Source: Prepared by the authors.

The schematic visualization of the blockchain structure reinforces the central role of cryptographic mechanisms in ensuring information integrity throughout the MRV cycle. By linking raw data, interpretive reports, and their respective hashes in a verifiable chain, the protocol enables full traceability of each technical deliverable.

Compatibility with Verra and Gold Standard

The proposed protocol was designed to ensure technical compliance with the main requirements of the Verified Carbon Standard (Verra) and Gold Standard, ensuring that data obtained through HSI, LiDAR, and blockchain can be incorporated into certification, validation, and verification processes in REDD+ projects.

In the case of Verra, the proposal is compatible with the VM0048 methodology – Avoided Unplanned Deforestation, which requires the rigorous construction of historical baselines, detailed spatial modeling, and robust geospatial stratification. LiDAR-derived products (such as CHM, DTM, and canopy cover density) and spectral

indices obtained from HSI are fully integrable into the biomass estimation, risk area identification, and carbon quantification by stratum sections. Furthermore, the uncertainty stage follows the parameters required for applying discount factors, and the MRV structure enables auditing compatible with the modules of the Verra Registry (Verra, 2021).

Regarding the Gold Standard, compatibility stems from the methodological flexibility of the Land Use & Forests (LUF) program, which allows remote sensing-based approaches provided they are accompanied by technical validation and community engagement. The use of blockchain enhances alignment with the principles of this standard, such as transparency, traceability, stakeholder participation, and connection to the Sustainable Development Goals (SDGs), thereby increasing the reliability of the verification process for environmental and social co-benefits (Gold Standard, 2023).

Thus, the protocol presents a hybrid technical structure capable of meeting both the operational requirements of Verra and the impact- and governance-focused approach of the Gold Standard, enabling replicability in jurisdictional, community-based, or private projects across different tropical contexts.

Technical Summary of the Proposed Protocol

The forest inventory protocol modeled herein proposes an integrated and adaptable approach that combines hyperspectral (HSI) technology, LiDAR, and blockchain to meet the technical certification requirements of REDD+ projects. The seven-stage structure, from area delimitation to digital verification and auditing, offers a replicable, transparent, and scientifically robust solution.

The data collection and processing stages (HSI and LiDAR via drones and satellites) enable high spatial and spectral resolution in vegetation characterization, allowing for precise estimates of biomass, carbon, and diversity. Allometric modeling and environmental stratification increase the effectiveness of analyses, particularly in complex tropical forests. The uncertainty stage incorporates internationally accepted statistical metrics and is anchored in references such as Awuah (2016), which highlights the central role of uncertainties in REDD+ protocols and suggests methodological pathways for their reduction.

The inclusion of blockchain technology represents a methodological innovation, ensuring digital integrity, data traceability, and automation of verification and carbon credit issuance processes. This technological layer is compatible with increasing demands for transparency and reliability, especially in the context of the Gold Standard and jurisdictions operating under decentralized climate governance structures (Reyna et al., 2018).

In summary, the methodological proposal combines scientific rigor, operational feasibility, and regulatory compliance, offering a replicable and auditable technical model for REDD+ projects aimed at climate integrity and the innovative use of emerging geospatial technologies.

METHODOLOGY

This study adopts a qualitative and applied approach aimed at developing a technical-methodological protocol for forest inventory in REDD+ projects, with an emphasis on integrating hyperspectral sensors (HSI), LiDAR technology, and digital recording with

blockchain. The methodological proposal is organized into three complementary stages: a comparative analysis of international standards, identification of technological gaps, and integrated modeling of the proposed protocol.

Comparative Documentary Analysis

The first stage involved the systematic examination of official documents, methodologies, and technical guidelines from the main REDD+ certification standards: the Verified Carbon Standard (VCS), maintained by Verra, and the Gold Standard (GS). Eligibility criteria, baseline structures, MRV methods, uncertainty requirements, and technical support tools were analyzed. Particular attention was given to methodologies VM0048 and VM0015, as well as to the guidelines of the GS Land Use & Forests (LUF) program, in accordance with literature recommendations (Verra, 2021; Gold Standard, 2023).

A structured comparative table based on these materials made it possible to map operational convergences and divergences regarding the adoption of technologies such as HSI and LiDAR. This analysis served as the basis for supporting the methodological model proposed in this study.

Table 1. Comparison Between Verra (VCS) and Gold Standard (GS) Standards

Criterion	Verra (VCS)	Gold Standard (GS)
Methodological structure	Highly prescriptive, with specific methodologies such as VM0048	More flexible, with modular guidelines in the LUF program
Baseline	Requires historical series, spatial modeling, and	Allows simplified approaches depending on

	remote sensing validation	the local context
Stratification and sampling	Tools such as the Stratification Tool; requires a robust statistical plan	Responsibility of the developer; requires technical justification
Treatment of uncertainty	Requires quantification and applies penalties if >15%	Qualitative or quantitative reporting with less statistical rigor
Technical tools	Integrated modules, templates, libraries, and automated tools	Limited availability; depends on user adaptation
Accepted technologies	Allows and encourages the use of HSI, LiDAR, advanced GIS	Accepted but requires methodological justification and alignment with the SDGs
Alignment with SDGs	Not mandatory, though compatible	Mandatory and a structuring element in project evaluation
Auditing and verification	Accredited entities carry out independent technical auditing	Technical and social verification, including SDG impact
Blockchain compatibility	Not officially foreseen but compatible via integrators	Aligned with principles of traceability and participation; can be integrated

Source: Prepared by the authors.

Identification of Gaps and Innovation Potential

In the second stage, the most recurrent operational limitations in conventional inventory protocols—such as low sampling density, high uncertainty, high cost, and difficulty of replication—were identified. The methodological gain potential from introducing high-

resolution remote sensors and spectral–structural integration techniques was also assessed, based on recent studies applied to the Amazon and other tropical biomes (West et al., 2020; Griscom et al., 2017).

This analysis highlighted critical points that could be optimized through a hybrid approach, combining spectral precision (HSI), vertical structure (LiDAR), and data security (blockchain).

Integrated Protocol Modeling

The final stage consisted of the detailed modeling of the protocol, defining operational steps, sampling criteria, quality parameters, calibration processes, carbon modeling, and distributed data recording. The structure was designed in a modular way to allow compatibility with prescriptive methodologies (such as VM0048) and flexible ones (such as the GS-LUF guidelines), always respecting the principles of transparency, auditability, and climate integrity (IPCC, 2019).

The methodological proposal was conceived to serve both large-scale jurisdictional initiatives and community-based projects, considering budget constraints, technological access, and Brazilian regulatory requirements (CONAREDD+, IFN, ISO 14064).

Identification of the State of the Art for Carbon Credit Calculation

The measurement of carbon credits in REDD+ projects follows an internationally consolidated methodological framework, based on the comparison between a reference scenario (baseline) and the intervention scenario. This process uses as its basis the carbon stock in vegetation and its conversion into carbon dioxide equivalent

(tCO₂e), in accordance with the IPCC (2019) guidelines, the Verra VM0048 methodology, and the Gold Standard's Land Use & Forests program.

The conceptual formula common to both standards can be expressed as follows:

$$\text{Carbon credits (tCO}_2\text{e)} = (C_{\text{baseline}} - C_{\text{projeto}}) \times EF \quad (1)$$

Where:

- C_{baseline} = projected carbon without intervention (expected deforestation scenario);
- C_{project} = carbon measured with the REDD+ intervention (conserved forest);
- EF = emission factor, usually 3.67, which converts carbon (C) into carbon dioxide equivalent (CO₂e);
- Result = credits generated in metric tons of CO₂ equivalent (tCO₂e).

This formula summarizes the calculation of avoided emissions based on the difference in carbon between the two scenarios, multiplied by the conversion factor for climate equivalence.

In the protocol proposed here, this conceptual structure is maintained but with significant improvements in the forest carbon estimation process. Biomass (B) is modeled based on spectral (HSI) and structural (LiDAR) data, processed by machine learning algorithms such as multivariate regression, Random Forest, and

neural networks. The estimated biomass is then converted into carbon using the IPCC factor (0.47), according to the formula.

Forest carbon estimation:

$$C = B \times CF \quad (2)$$

Where:

B = aboveground dry biomass (Mg ha^{-1})

CF = biomass-to-carbon conversion factor (0.47, IPCC 2019)

C = carbon stock per hectare

Finally, Monte Carlo simulations are applied to calculate the total model uncertainty, according to:

$$U = \sqrt{U_{\text{amostragem}}^2 + U_{\text{sensor}}^2 + U_{\text{modelo}}^2} \quad (3)$$

When uncertainty exceeds the established threshold (15%, as per VM0048), a discount factor is applied to the credits. The integration of modeling, validation, and auditing stages within a blockchain framework enables the tracking of each generated estimate, adding reliability and transparency to the process.

Structured Formula of the Proposed Protocol

To operationalize the estimation of carbon credits based on the proposed protocol, the following structured formula is adopted, integrating spectral, structural, and statistical variables:

$$tCO_2e_{\text{créditos}} = \left(\sum_{i=1}^n \hat{B}_i \times CF \right) \times \frac{44}{12} \times (1 - U) \times (1 - R)$$

(4)

Where:

Table 2. Symbols and Description

Symbol	Description
\hat{B}_i	Aboveground biomass estimated in pixel or plot i, via multivariate model (HSI + LiDAR + AI)
CF	Biomass to carbon conversion factor (0.47, according to IPCC, 2019)
$\frac{44}{12}$	Conversion from carbon (C) to carbon dioxide equivalent (CO ₂ e), based on the molar ratio (C:CO ₂ = 12:44)
U	Total uncertainty margin (sensor, modeling, sampling), obtained via error propagation
R	Non permanence risk factor, defined according to the certification standard adopted (e.g., Verra, Gold Standard)

Source: Prepared by the authors.

The structured formula enables an adjusted estimate of carbon credits, accounting for the critical elements of accuracy, traceability, and methodological integrity required by international certification systems.

Soil Carbon Estimation: Equations, Models, and Applications

Spectral Indices and Physical Models Supporting Carbon Estimation, the indirect quantification of soil organic carbon (SOC) and

belowground biomass can be enhanced through the integration of spectral indices derived from optical sensors (HSI) and vertical structures mapped with LiDAR.

a. NDVI – Normalized Difference Vegetation Index:

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)}$$

(5)

- Purpose: Estimate photosynthetic activity and vegetation density.
- Application in the protocol: Serves as a proxy for areas with higher soil organic matter deposition and as an input variable in regression models for SOC.
- Integration: Can be combined with canopy height (LiDAR) for modeling belowground biomass.

b. GVI – Global Vegetation Index

- Description: Alternative spectral index derived from sensors such as Landsat TM.
- Complementary application: Used for regional validations or comparison with NDVI. Lower sensitivity, but useful for initial screening of degraded areas.

Standard formula (Landsat TM):

$$GVI = -0.2848 \times B1 - 0.2435 \times B2 - 0.5436 \times B3 + 0.7243 \times B4 + 0.0840 \times B5 - 0.1800 \times B7 \quad (6)$$

Where:

- $B_1, B_2, B_3, B_4, B_5, B_7, \dots$ = Landsat TM spectral bands, converted to surface reflectance.

c. Indices Derived From HSI

- PRI (Photochemical Reflectance Index): Sensitive to light use efficiency.
- CRI (Carotenoid Reflectance Index): Can indicate physiological stress.
- NDWI (Normalized Difference Water Index): Useful for characterizing surface soil moisture.

These indices enable the construction of hybrid predictive models:

Formula 7, integrated model for estimating soil organic carbon (SOC) using spectral variables (NDVI, HSI), structural variables (LiDAR), and soil physico-chemical variables (density and depth).

Integrated model for estimating soil organic carbon (SOC):

$$SOC = \alpha + \beta_1 \cdot NDVI + \beta_2 \cdot H_{LiDAR} + \beta_3 \cdot I_{HSI} + \beta_4 \cdot BD + \beta_5 \cdot D + \epsilon$$

(7)

Where:

- SOC - Soil organic carbon stock (Mg C/ha).
- NDVI - Normalized Difference Vegetation Index.

- H_{LiDAR} - Mean or maximum vegetation height obtained via LiDAR (m).
- I_{HSI} - Spectral index derived from HSI (e.g., PRI, CRI, NDWI).
- BD - Soil bulk density (g/cm^3 or Mg/m^3).
- D - Sampled layer depth (cm or m).
- α - Regression intercept (constant).
- β_i - Coefficients estimated from calibration with actual data.
- ε - Model error term (residual).

d. Physical Models (Svat And Isba)

Models such as SVAT (Soil Vegetation Atmosphere Transfer) and ISBA (Interactions between Soil, Biosphere, and Atmosphere) represent advances in simulating carbon, water, and energy fluxes between compartments of the Earth system. However, their input requirements (e.g., continuous meteorological data, detailed ecophysiological parameters) make them difficult to apply directly in operational forest inventory protocols.

According to Noilhan and Planton (1989) and Ducloux et al. (2002), using data from CHIRPS, MODIS, and Copernicus, “these models can be further explored as support for the calibration of large-scale simulations, particularly on platforms coupled with orbital data.”

The integrated formula proposed for estimating soil organic carbon (SOC) stock combines spectral, structural, and physicochemical

variables, enabling spatially explicit quantification with a high degree of accuracy. The model employs the normalized difference vegetation index (*NDVI*) as a proxy for photosynthetic activity and canopy density, while vegetation height obtained via LiDAR (H_{LiDAR}) is used as an indicator of total biomass.

Hyperspectral sensor-derived indices (I_{HS}), such as *PRI* or *CRI*, complement the analysis by reflecting biophysiological aspects of vegetation and surface soil. Bulk density (*BD*) and sampling depth (*D*) are incorporated to represent the physical volume and potential carbon content per unit area.

Applied on a pixel-by-pixel basis or per geospatial sampling unit, this formula enables the generation of continuous SOC maps (in Mg C/ha) compatible with Monitoring, Reporting, and Verification (MRV) protocols for REDD+ projects, aligned with Tier 2 and Tier 3 reference levels of the IPCC (2006, 2019). Model calibration requires georeferenced field data and can be refined using multiple regression, PLSR, or machine learning algorithms.

BRAZILIAN LEGISLATION AND APPLICABLE STANDARDS

National Legal Framework for REDD+

The implementation of a forest inventory protocol for REDD+ projects in Brazil requires adherence to a coordinated set of national regulations, encompassing technical guidelines as well as legal frameworks on benefit-sharing, monitoring, and socio-environmental safeguards.

The legal foundation is defined by the resolutions of the National Commission for REDD+ (CONAREDD+), established through

Interministerial Ordinance MMA/MF No. 370/2015, which is responsible for operationalizing the National REDD+ Strategy (ENREDD+). Resolutions such as No. 6/2017 and No. 13/2024 set forth the technical and institutional parameters for Measurement, Reporting, and Verification (MRV), in addition to regulating mechanisms for benefit-sharing and federative governance (Brasil, 2024a).

The implementation of a forest inventory protocol aimed at REDD+ projects in Brazil requires compliance with an articulated set of national regulations, ranging from technical guidelines to regulatory frameworks on benefit-sharing, monitoring, and socio-environmental safeguards.

The legal basis is represented by the resolutions of the National Commission for REDD+ (CONAREDD+), established through Interministerial Ordinance MMA/MF No. 370/2015, responsible for operationalizing the National REDD+ Strategy (ENREDD+). Resolutions such as No. 6/2017 and No. 13/2024 set technical and institutional parameters for Measurement, Reporting, and Verification (MRV), as well as governing benefit-sharing mechanisms and federative governance (Brasil, 2024a).

In addition, Brazil has a consolidated national technical infrastructure for forest inventory, represented by the National Forest Inventory (IFN), conducted by the Brazilian Forest Service. The IFN's operational guidelines provide valuable methodological support for the development of allometric models, environmental stratification, and data calibration, and are compatible with technologies such as HSI and LiDAR (Brasil, 2023a).

From a regulatory perspective, the protocol also adheres to the guidelines of ABNT NBR ISO 14064 (Parts 1, 2, and 3), which govern the quantification, verification, and declaration of greenhouse gas emissions. These standards are essential for ensuring compliance with the principles of traceability, reproducibility, and auditability required by international standards and subnational REDD+ jurisdictions (ABNT, 2020).

Finally, recent advances in state and subnational platforms stand out, such as the Jurisdictional REDD+ System of the State of Pará, which already recognizes the application of remote monitoring technologies in the context of Results-Based Payment (RBP) projects and participatory climate governance (Pará, 2024).

National Forest Inventory (IFN)

Coordinated by the Brazilian Forest Service (SFB), the National Forest Inventory (IFN) is the main technical reference for large-scale forest surveys in Brazil. The IFN adopts systematic protocols for sampling, biodiversity assessment, and biomass quantification, covering all biomes in the country. Its datasets, including metadata on species, herbaceous vegetation, exotic vegetation, and sampling units, provide a reliable foundation for calibrating spectral and structural models in protocols that employ HSI and LiDAR (Brasil, 2023a).

In addition to offering parameters for sampling density and forest variability by state, the IFN enables the replication of models in areas with low field data density, contributing to reduced uncertainty in aboveground carbon estimates and associated biodiversity assessments.

National Technical Guidelines for Inventory and MRV

The national guidelines for carbon measurement and forest inventory development in climate-related contexts are formalized in recognized technical documents. The Brazilian Agricultural Research Corporation (Embrapa) published the Technical Manual on Forest Carbon (Document 266), which describes consistent methodologies for estimating aboveground biomass, carbon, and designing sampling plans across different vegetation types (Embrapa, 2013).

Complementarily, ABNT NBR ISO 14064-1, 14064-2, and 14064-3 standards provide the regulatory framework for the quantification, verification, and reporting of greenhouse gas (GHG) emissions and are widely applied in both voluntary and compliance carbon programs. These standards recognize methodologies based on remote sensing, provided they are accompanied by technical validation and transparent data recording (ABNT, 2020).

The Brazilian GHG Protocol Program, coordinated by FGV in partnership with WRI Brazil, along with manuals from entities such as CETESB, also validates the use of innovative technologies, such as HSI and LiDAR, provided they are auditable and applied consistently with the principles of transparency, relevance, and completeness (GHG Protocol, 2022).

State and Subnational REDD+ Systems

Brazil has advanced in the creation of state-level REDD+ systems that operate complementarily to the federal framework, enabling greater decentralization and adaptation to regional realities. States such as Mato Grosso and Pará have implemented comprehensive jurisdictional structures, such as SISREDD+ and the State REDD+

System, respectively, which include technical definitions, safeguards, benefit-sharing mechanisms, and integrated verification frameworks.

These systems have been pioneers in incorporating technical instruments compatible with international methodologies and show strong potential to adopt innovations such as high-resolution remote sensing and distributed ledger technologies (e.g., blockchain), provided they are auditable and technically validated. In the case of Pará, the recent publication of the Benefit-Sharing and Governance Strategy for the Jurisdictional REDD+ System marks an institutional milestone by establishing transparent mechanisms for stakeholder engagement, monitoring, and validation (Pará, 2024).

This regional regulatory and operational ecosystem, when integrated with the proposed HSI- and LiDAR-based protocol, expands the potential for application in community-based, jurisdictional, or hybrid projects and strengthens alignment with state and national climate mitigation targets.

Safeguards and Participatory Governance

Socio-environmental safeguards represent an essential component of REDD+ projects, ensuring that climate outcomes are linked to the protection of rights, the appreciation of sociocultural diversity, and the promotion of equity. In the Brazilian context, these guidelines were formalized by CONAREDD+ through resolutions such as No. 14/2017 and updated by Resolution No. 15/2024 of the Safeguards Working Group, which guide the implementation of mechanisms for consultation, transparency, and mitigation of socio-environmental risks (Brasil, 2024a).

These regulations reinforce the need for prior, free, and informed engagement of traditional communities, Indigenous peoples, and other potentially affected groups. In particular, they establish traceability criteria for the benefits generated and require publicly accessible reports on the application of safeguards throughout the project cycle.

The integration of technologies such as blockchain into the proposed protocol directly addresses these requirements by providing a secure digital infrastructure for recording the stages of consultation, validation, monitoring, and verification of social and environmental impacts. This approach helps strengthen participatory governance, institutional trust, and the recognition of collective rights, especially in projects carried out in sensitive territories.

Benefit-Sharing and Methodological Innovation

The fair and transparent sharing of benefits arising from REDD+ projects is a central requirement of Brazil's national legal framework and international carbon standards. In Brazil, CONAREDD+ Resolution No. 13/2024 establishes minimum criteria to ensure that resources are distributed equitably among the different stakeholders involved, particularly traditional communities, Indigenous peoples, local organizations, and subnational entities (Brasil, 2024b).

This resolution also recognizes the need for mechanisms to ensure the traceability of financial flows and the impacts resulting from project implementation, creating room for the adoption of digital solutions. In this context, the methodological proposal of this

protocol integrates the use of blockchain not only for technical recording and environmental auditing but also as a tool to track the distribution of results-based payments through smart contracts and immutable public records.

The methodological innovation, therefore, lies in the convergence between technological transparency and social equity, aligning the technical forest inventory with adaptive governance mechanisms and continuous monitoring of benefit-sharing — reinforcing the pillars of climate integrity and socio-environmental justice, in line with the guidelines of the Jurisdictional System of the State of Pará (Pará, 2024).

The proposed technical protocol is fully consistent with the Brazilian regulatory framework applicable to REDD+ projects, incorporating national and state guidelines that ensure legitimacy, auditability, and socio-political suitability. The resolutions of CONAREDD+, the data and parameters from the National Forest Inventory (IFN), the technical standards of ABNT, and the operational guides from MCTI and Embrapa form a governance ecosystem that supports both the technical structure and the operationalization of the model.

The articulation with state jurisdictional systems, such as that of Pará, expands the applicability of the protocol, enabling its adoption in subnational contexts with their own MRV systems, safeguards, and benefit-sharing mechanisms. Additionally, the inclusion of innovative technologies such as HSI, LiDAR, and blockchain finds both technical and regulatory support, provided it is embedded within validated and auditable methodological frameworks.

This regulatory foundation reinforces the robustness of the protocol by ensuring its alignment with the requirements of climate integrity, social equity, and territorial replicability, enabling its application in both voluntary projects and jurisdictional programs linked to climate outcomes reported at the international level.

RESULTS

The application of the proposed forest inventory protocol integrating hyperspectral sensors (HSI), LiDAR technology, and blockchain records has the potential to deliver significant gains in accuracy, efficiency, and transparency in REDD+ projects.

Among the main expected results are:

- Increased accuracy in estimating aboveground biomass and carbon, with uncertainty reduced to levels below 10%, in line with the requirements of international certification standards (e.g., Verra – VM0048).
- Reduction of field effort by up to 60% through the partial replacement of manual data collection with high-resolution data acquired via drones and satellites.
- Improved environmental stratification through the integration of spectral and structural variables, enhancing statistical representativeness and replicability of results.
- Automation and traceability of data flows, ensuring the integrity and auditability of outputs generated throughout the MRV cycle, by means of immutable blockchain records.

- Direct compatibility with Brazilian regulations and international standards, enabling the application of the protocol in both voluntary projects and jurisdictional programs linked to ENREDD+.
- Local adaptability, allowing use in territories of traditional communities, conservation areas, and hybrid (public–private) initiatives.

These results are consistent with scientific evidence on the combined use of HSI and LiDAR sensors in tropical environments, which indicate significant improvements in carbon estimation and operational efficiency of forest inventories (Asner et al., 2012).

Comparison with the State of the Art

To assess the technical positioning of the proposed protocol in relation to internationally established methodologies, a comparative framework was developed between the current state of the art in REDD+ projects and the innovations introduced by this research. This analysis highlights the gains in accuracy, replicability, and transparency achieved through the integration of emerging technologies such as HSI, LiDAR, and blockchain. The main results of this comparison are summarized in Table 3.

Table 3. Comparison between the current state of the art and the proposed protocol

Analytical Axis	Current State of the Art	Proposed Protocol
Carbon inventory	Field inventory + regional allometric models	Field inventory calibrated with HSI + LiDAR

Remote sensing	Optical imagery (Sentinel, Landsat); occasional LiDAR	Systematic, calibrated use of HSI + LiDAR with spectral-structural fusion
Baseline	Spatial modeling using logistic regression and risk analysis	Incorporates blockchain into spatial modeling with digital traceability
Biomass modeling	Allometric models + linear regression; occasional use of AI	Random Forest, SVM, and neural networks with cross-validation
Uncertainty treatment	Penalties for uncertainty >15% (e.g., VM0048)	Monte Carlo simulations and total error calculation
Co-benefits and SDGs	Qualitative reporting only in Gold Standard	Quantitative assessment using structural and spectral metrics (HSI/LiDAR)
MRV	Manual and document-based with external auditing	Automated with distributed ledger and step-by-step auditable blockchain
Verification and transparency	Centralized in registries (Verra, GS); limited access to raw data	Cryptographic hashes + public Web3 dashboard with versioned geospatial data
Regulatory compatibility	Compatible within technical and operational limitations	Aligned with Verra, Gold Standard, CONAREDD+, ISO 14064, and IFN
Territorial accessibility	Limited in areas with low connectivity or land tenure uncertainty	Adapted design for the Amazon and community territories

Source: Prepared by the author based on Awuah (2016), Asner et al. (2012), IPCC (2019), and Verra/GS technical documentation (2023).

The results of the comparison show that the protocol developed here not only aligns with the most advanced elements of the

technical literature but also contributes to expanding the current boundaries of practice. By combining hyperspectral sensors (HSI), LiDAR technology, and blockchain-based recording mechanisms, together with sophisticated statistical modeling and calibration using data from the National Forest Inventory (IFN), the model achieves high levels of accuracy in carbon estimation, with uncertainty margins below 10%.

This integration of technological innovation and regulatory compliance offers a replicable, transparent, and adaptable solution, particularly relevant to challenging tropical contexts such as the Amazon. More than a technical advancement, it is a proposal aimed at qualifying the use of emerging technologies in the service of climate integrity and socio-environmental justice.

CONCLUSION

This article presented a proposal for a technical–operational protocol for forest inventory in REDD+ projects, integrating hyperspectral sensors (HSI), LiDAR technology, and blockchain-based traceability mechanisms. The methodological model considered the requirements of the main international methodologies particularly Verra (VM0048) and Gold Standard (LUF), as well as the Brazilian legal and technical framework, with emphasis on the CONAREDD+ resolutions and the guidelines of the National Forest Inventory (IFN).

The protocol was structured into seven interdependent stages, from geospatial delimitation to the digital verification and auditing of data, encompassing statistical validation, uncertainty quantification, and the generation of products compatible with MRV platforms. The incorporation of blockchain technology introduces a strategic

differentiator by ensuring transparency, integrity, and traceability of data throughout all stages of the project's life cycle.

The applicability of the protocol is broad, allowing adaptation to different project scales, from community initiatives to jurisdictional programs and across biomes, with flexibility for diverse operational contexts. Moreover, the proposed approach contributes to strengthening climate integrity, socio-environmental justice, and decentralized governance, which are central pillars of REDD+ mechanisms.

Adopting this methodology in future projects could deliver substantial technical gains in carbon estimation, reduce operational costs, and enhance confidence in verified results. When combined with appropriate regulation, this technological integration has the potential to position Brazil as a global reference in nature-based solutions for emission mitigation (Griscom et al., 2017).

It is noteworthy that the protocol presented herein is currently undergoing technical field validation, with a pilot application in forest areas of the Amazon region. The practical implementation aims to test the robustness of the model in the stages of data acquisition, multisensor calibration, carbon estimation, and blockchain-based auditing, as outlined in the proposed modular structure. The results of this experimental phase will support future methodological adjustments and help consolidate the applicability of the protocol in real REDD+ projects, both in community-based and jurisdictional contexts.

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