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Filipe Lins dos Santos
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Rua Josias Lopes Braga, n. 437, Bancários, João Pessoa - PB - Brasil
website: www.periodicojs.com.br
instagram: @periodicojs

Capítulo 30

DIGITAL MRV AND ENVIRONMENTAL INTEGRITY IN REDD+: A SOCIOTECHNICAL FRAMEWORK LINKING TECHNICAL PERFORMANCE AND INSTITUTIONAL GOVERNANCE

DIGITAL MRV AND ENVIRONMENTAL INTEGRITY IN REDD+: A SOCIOTECHNICAL FRAMEWORK LINKING TECHNICAL PERFORMANCE AND INSTITUTIONAL GOVERNANCE

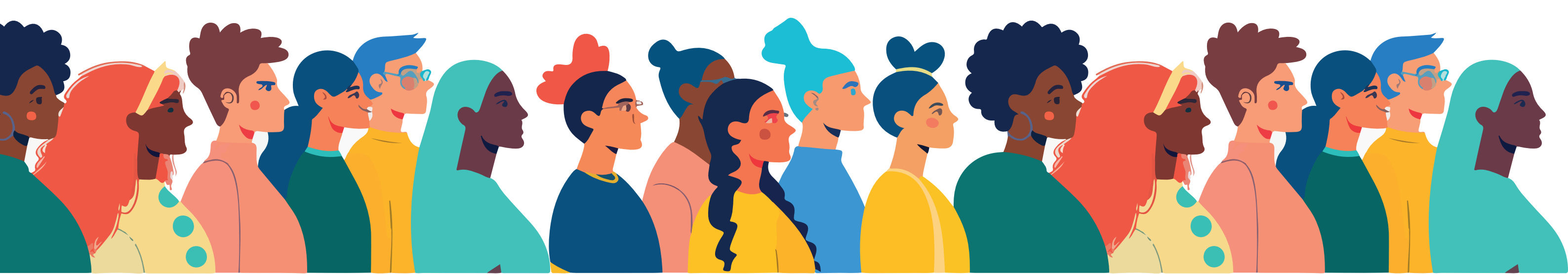
José Luiz Gondim dos Santos[1]

Henrique Alberto Leite Anastácio[2]

Abstract: Forest-based climate policies increasingly rely on digital measurement, reporting, and verification (MRV) systems, yet technical performance alone may not ensure the credibility of the information they produce. This study examines how digital and artificial intelligence capabilities interact with technical performance and institutional governance in REDD+ MRV. We conducted a comparative conceptual and methodological study of six functionally heterogeneous analytical units - Google Earth Engine, Global Forest Watch, Planet Labs, Sylvera, MapBiomas, and INPE (PRODES/ DETER) - using secondary scientific, technical, and institutional evidence. We developed the MRV-related Environmental Integrity Index (MRV-EII), combining accuracy, consistency, transparency, verifiability, and traceability through Analytic Hierarchy Process weighting, and tested its sensitivity under alternative weighting scenarios. MRV-EII scores ranged from 0.65 to 0.99. Accuracy and consistency showed relatively limited dispersion, whereas transparency, verifiability, and traceability varied more strongly across units and contributed more strongly to differences in aggregate scores under the main weighting structure. Rankings remained broadly stable across weighting scenarios and unchanged after excluding accuracy, although units characterized by stronger technical than

1 PhD candidate in Biodiversity and Biotechnology at the Federal University of Acre (UFAC), Rio Branco, Acre, Brazil. E-mail: jose.gondim@sou.ufac.br. ORCID: 0000-0003-1705-7268. Lattes CV: http://lattes.cnpq.br/9127135353294284

2 Master's student in Health Sciences, biologist, and undergraduate student in Forest Engineering at the Federal University of Acre (UFAC), Rio Branco, Acre, Brazil (2026). E-mail: henrique.anastacio@sou.ufac.br. ORCID: 0009-0003-2935-1592. Lattes CV: http://lattes.cnpq.br/8334147535345821



institutional performance were more sensitive to technical weighting. An illustrative application to Acre, Brazil, showed that the framework can be operationalized in a jurisdictional configuration without constituting program-level validation. The findings support a sociotechnical interpretation of MRV integrity: greater digital capability does not necessarily translate into greater integrity unless technical performance is accompanied by institutional conditions that make results transparent, verifiable, and traceable.

Keywords: REDD+; digital MRV; environmental integrity; forest monitoring; institutional governance; carbon markets.

Introduction

The credibility of forest-based climate policies depends on the capacity to translate observed changes in forest cover, biomass, and carbon stocks into measurable, verifiable, and institutionally recognized evidence.

Within REDD+, this function is performed by measurement, reporting, and verification (MRV) systems, which support the quantification of results and their potential linkage to results-based payments or carbon markets. The Warsaw Framework consolidated this role by establishing that national forest monitoring systems should produce transparent information that is consistent over time and suitable for measurement, reporting, and verification, with procedures capable of supporting the technical assessment of results (UNFCCC, 2013a, 2013b).

MRV integrity therefore forms part of the institutional infrastructure linking forest monitoring, climate policy, and economic value.

This issue has become increasingly important as the integrity of carbon market mechanisms has come under global scrutiny. Differences in baselines, accounting rules, additionality, and unit quality can substantially alter the outcomes attributed to climate interventions (Schneider and La

Hoz Theuer, 2019). In forest conservation projects, recent assessments show that estimated reductions in deforestation may diverge from observed effects when alternative counterfactuals are used, underscoring the importance of measurement quality for the credibility of carbon credits (West et al., 2023).

Although environmental integrity is broader than MRV, the reliability of the information used to measure and verify results is one of its fundamental conditions.

In parallel, forest monitoring has undergone rapid technological transformation. Remote-sensing time series have enabled forest-cover change to be tracked at global scale (Hansen et al., 2013), while cloud computing, machine learning, deep learning, and high-resolution imagery have expanded the capacity to process data and detect environmental change. In the Amazon, for example, deep-learning methods combined with Planet NICFI imagery have enabled high-resolution mapping of different forms of forest degradation (Dalagnol et al., 2023). More recently, digital MRV architectures have integrated remote sensing, carbon modeling, and time-series data within frameworks designed to measure and verify forest carbon stocks (Anderson et al., 2026).

The expansion of these capabilities, however, introduces a distinct problem. As algorithms, computational infrastructures, and distributed data sources play a greater role in producing estimates, the need also increases to understand how results were generated, which procedures were used, and to what extent those results can be reproduced or subjected to independent verification.

This problem is consistent with the broader literature on algorithmic governance, in which computational performance and accountability are related but non-equivalent attributes (Kroll et al., 2017). Likewise, the literature on explainable artificial intelligence shows that high predictive performance does not eliminate the need for transparency and scrutiny of automated decision-making processes (Barredo Arrieta et al., 2020).

This tension between measurement and governance predates the current expansion of artificial intelligence. Gupta et al. (2012) argue that REDD+ MRV systems are not exclusively technical processes, because carbon accounting also involves choices concerning standardization, knowledge production, and the accountability of actors who produce and validate information. The concept of carbon accountability therefore brings measurement and governance together and provides a foundation for understanding digital MRV systems as sociotechnical infrastructures in which the credibility of estimates depends both on their technical production and on the institutional conditions for scrutiny and accountability.

The challenge is particularly relevant in tropical countries, where MRV capacities remain heterogeneous and extend beyond the availability of data or remote-sensing technologies. Romijn et al. (2012) identified substantial cross-country differences in the capacity to implement national monitoring systems for REDD+. In an assessment of 13 countries, Ochieng et al. (2016) identified a particularly relevant asymmetry: technical methods were relatively advanced, whereas administrative capacity and good-governance requirements were less developed. More recently, Yang et al. (2025) reinforced the view that REDD+ readiness depends on MRV capacities that combine technical and institutional components.

This trajectory suggests that expanding technological capacity, including through digitalization and artificial intelligence, does not automatically overcome limitations related to governance, institutional continuity, and the verifiability of information.

In Latin America, the relationship between technology and institutions unfolds in settings characterized by the high climatic significance of forests and complex systems of territorial governance. Evidence from Brazil, Mexico, and Ecuador shows that REDD+ institutionalization depends on coordination among forest policies, rural development, and governance arrangements, and that the availability of technical instruments does not eliminate institutional conflicts or problems of policy coherence (Bastos Lima et al., 2017).

In this context, MRV systems must function not merely as observation mechanisms, but as infrastructures capable of producing information recognized across multiple actors and scales of governance.

Brazil provides a particularly relevant setting for this transformation. The country has developed a remote-sensing-based forest monitoring infrastructure in which public systems such as PRODES and DETER perform complementary functions of annual deforestation mapping and near-real-time alert generation.

The evolution of DETER expanded the capacity to detect changes in the Amazon and strengthened its use in support of environmental enforcement (Diniz et al., 2015). In parallel, collaborative initiatives such as MapBiomas began producing annual land-use and land-cover time series for all Brazilian biomes using Landsat imagery, cloud processing, and classification algorithms, thereby expanding the diversity of information sources available for environmental analysis and public policy (Souza Jr. et al., 2020).

At the same time, REDD+ in Brazil has a strong multilevel governance component. Amazonian states have developed their own jurisdictional arrangements linking subnational policies, climate finance, and national and international REDD+ frameworks. Acre, Amazonas, Mato Grosso, Pará, and Amapá, among others, have participated in this institutional construction, illustrating the growing role of subnational jurisdictions in Brazilian climate governance (Gueiros et al., 2023).

The coexistence of public systems, collaborative platforms, commercial providers, computational infrastructures, and jurisdictional arrangements makes Brazil a particularly relevant context in which to investigate how technological capabilities and institutional attributes combine in the production of MRV information.

Despite these advances, two strands of the literature remain only partially connected. On the one hand, forest-monitoring studies focus on accuracy, spatial resolution, frequency, algorithms, and processing capacity (Hansen et al., 2013; Dalagnol et al., 2023; Anderson et al., 2026). On the other hand, the literature on REDD+ and carbon markets emphasizes environmental integrity, governance, accounting, and institutional credibility (Schneider and La Hoz Theuer, 2019; West et al., 2023).

This fragmentation makes it difficult to assess situations in which systems exhibit high technical performance but different levels of transparency, verifiability, and traceability. The scientific problem, therefore, is not merely whether digital technologies improve forest monitoring, but under what conditions technological capabilities can be converted into credible and institutionally verifiable environmental evidence.

This study starts from the proposition that MRV-related integrity is a sociotechnical phenomenon: technological performance is necessary but not sufficient, and its contribution depends on institutional conditions that allow the resulting evidence to be understood, verified, and reconstructed. The study therefore asks: How do digital and artificial intelligence capabilities interact with technical performance and institutional attributes to shape MRV-related integrity in REDD+?

The objective is to analyze this relationship across different configurations of the digital forest-monitoring ecosystem. To this end, the study compares six functionally heterogeneous units - Google Earth Engine, Global Forest Watch, Planet Labs, Sylvera, MapBiomas, and INPE (PRODES/DETER) - and develops the MRV-related Environmental Integrity Index (MRV-EII), comprising Accuracy, Consistency, Transparency, Verifiability, and Traceability. The index is not intended to measure the full environmental integrity of REDD+ programs or carbon credits, but specifically the integrity associated with MRV infrastructure and information governance. An illustrative application to Acre is used to examine its operationalization in a jurisdictional setting.

The study makes a twofold contribution. Conceptually, it proposes understanding digital MRV systems as sociotechnical infrastructures in which technological capability and institutional governance are interdependent. Methodologically, the MRV-EII translates this relationship into a comparative framework that makes trade-offs among technical performance, transparency, verifiability, and traceability explicit. By shifting the focus from technology in isolation to the institutional conditions under which its outputs acquire credibility, the study seeks to contribute to debates on forest policy, jurisdictional REDD+, and carbon-market governance.

Methods

Study design

The study adopted a comparative conceptual and methodological design based on the scientific literature and technical and institutional documentation. The methodological objective was to operationalize integrity associated with digital measurement, reporting, and verification systems through the MRV-EII and to examine how technical performance and institutional attributes combine across different forest-monitoring configurations.

The analysis proceeded in four stages: (i) construction of the conceptual model based on the scientific literature and technical and institutional documentation; (ii) comparative documentary analysis of six units relevant to the digital MRV ecosystem; (iii) construction and application of the MRV-EII; and (iv) assessment of index sensitivity under alternative weighting structures and an additional robustness test. A jurisdictional application to the state of Acre was used solely to demonstrate the operationalization of the framework in a subnational REDD+ configuration.

Conceptual basis and documentary evidence

The literature was used to define the construct, identify its dimensions, and establish the analytical criteria, rather than as the object of a systematic review. This strategy is appropriate when the research problem integrates conceptually distinct fields and the purpose of the synthesis is to construct an analytical framework rather than to exhaustively estimate the findings of a homogeneous body of studies (Snyder, 2019).

The search was structured around four domains: (i) REDD+, MRV, and forest monitoring; (ii) artificial intelligence, machine learning, and remote sensing; (iii) environmental integrity and carbon accounting; and (iv) algorithmic governance, transparency, verifiability, and traceability. Web of Science, Scopus, and Google Scholar were consulted, complemented by documents from international organizations and by technical-methodological sources from the units analyzed. Selection prioritized studies with conceptual, methodological, or empirical contributions directly applicable to the construction of the framework or the operationalization of the MRV-EII dimensions. The search of the scientific literature and technical documentation was completed in August 2026.

The empirical evidence base comprised technical documentation, publicly available methodologies, scientific publications, institutional reports, and validation records related to the units examined. Documentary analysis was used to extract technical and institutional attributes in a systematic and traceable manner (Bowen, 2009).

Units of analysis and variables

Six units performing relevant functions in the digital forest-monitoring ecosystem were analyzed: Google Earth Engine, Global Forest Watch, Planet Labs, Sylvera, MapBiomas, and the Brazilian National Institute for Space Research (Instituto Nacional de Pesquisas Espaciais - INPE), through PRODES/DETER.

The units were purposively selected according to three criteria: participation in relevant forest-monitoring or carbon-measurement functions; availability of sufficient technical documentation; and diversity of technological and institutional configurations.

The units were not treated as equivalent organizations. They perform different functions involving data acquisition, processing, integration, monitoring, analysis, or validation. The comparison therefore does not seek to establish organizational superiority, but to identify how different configurations combine technical capabilities and governance attributes.

Six technical and operational characteristics were initially extracted: reported accuracy in selected applications, spatial resolution, temporal frequency, relative cost, analytical technology employed, and function within the MRV system. For the MRV-EII, the analysis focused on five dimensions: accuracy, consistency, transparency, verifiability, and traceability.

Technical-performance values derived from specific applications were not interpreted as universal properties of the platforms. They were used as comparative evidence within the scope of the documented applications.

Construction of the MRV-EII

The MRV-EII was developed as a composite index to operationalize integrity specifically associated with MRV infrastructure and governance. Its construction followed principles of construct definition, indicator selection, normalization, and aggregation commonly used in the development of composite indicators (OECD/European Union/EC-JRC, 2008).

The MRV-EII does not measure the overall environmental integrity of REDD+ programs or carbon credits. Additionality, permanence, leakage, and double counting remain outside its scope. The index evaluates technical and institutional conditions related to the reliability, auditability, and reproducibility of MRV information.

The MRV-EII was defined as:

$$\text{MRV-EII} = f(A, C, T, V, R)$$

The five dimensions were defined as follows:

- Accuracy (A): degree of correspondence between estimates or classifications and reference values or classes, operationalized through quantitative accuracy reported in selected applications;
- Consistency (C): methodological, operational, and temporal stability;
- Transparency (T): availability and clarity of methodological documentation;
- Verifiability (V): the extent to which methods and results can be independently

scrutinized, validated, or assessed;

- Traceability (R): the capacity to reconstruct the origin, history, transformations, and versions of data and procedures.

All components were expressed on a [0,1] scale. For Accuracy (A), reported percentage accuracy values were divided by 100. When a source reported a range, the midpoint between its lower and upper bounds was used. These values represent selected applications and were used as comparative proxies of technical performance rather than as universal properties of the units analyzed.

Consistency (C) was assessed on the basis of documentary evidence concerning temporal continuity, operational regularity, and methodological stability, using an ordinal [0,1] scale and allowing intermediate values when the evidence fell between adjacent levels.

Transparency, Verifiability, and Traceability were assessed on an ordinal scale with reference points of 0.25, 0.50, 0.75, and 1.00. A score of zero was reserved for the complete absence of the attribute when supported by documentary evidence. Intermediate values were permitted when the evidence fell between two adjacent levels.

Each qualitative score was linked to an explicit sequence: documentary evidence -> operational criterion -> classification -> score.

The corresponding matrix is presented in Supplementary Material S1, allowing the evidence underlying each scoring decision to be identified.

Weighting and aggregation

The five dimensions were aggregated using the Analytic Hierarchy Process (AHP), a method based on pairwise comparisons among criteria (Saaty, 2008).

For each unit j, the index was calculated as:

$$MRV - EII_j = \sum_{i=1}^{5} w_i x_{ij},$$

where is the normalized value of dimension for unit , and is its corresponding weight, subject to:

$$\sum_{i=1}^{5} w_i = 1.$$

The pairwise-comparison matrix was defined on the basis of the theoretical proposition that MRV integrity depends not only on technical performance but also on the ability to understand, verify, and reconstruct the processes that generate the estimates.

The procedure yielded the following weight vector:

$$W_{AHP} = (0.0546, 0.0978, 0.2825, 0.2825, 0.2825)$$

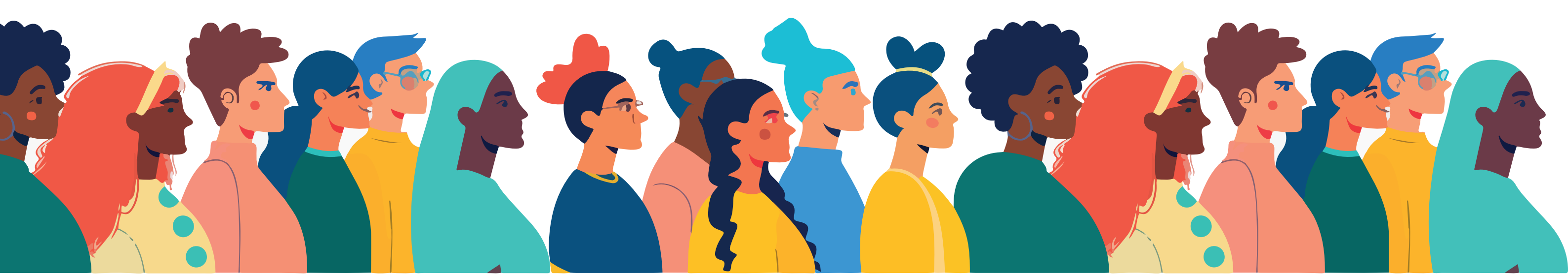
corresponding, respectively, to Accuracy, Consistency, Transparency, Verifiability, and Traceability.

The institutional dimensions therefore received a greater aggregate weight than the strictly technical dimensions. This weighting represents an explicit theoretical-normative choice rather than a result estimated from the performance of the units.

The logical consistency of the matrix was assessed using the AHP Consistency Ratio (CR). For the matrix used, , yielding and , below the conventional threshold of 0.10 (Saaty, 2008).

Sensitivity analysis and additional robustness test

The dependence of the results on the weights was examined using three alternative weighting



scenarios relative to the baseline AHP specification.

In the first scenario, all dimensions received equal weights:

$$W_{\text{equal}} = (0.20, 0.20, 0.20, 0.20, 0.20).$$

In the second scenario, Accuracy and Consistency received twice the individual weight assigned to the institutional dimensions:

$$W_{\text{technical}} = (A, C, T, V, R) = (0.2857, 0.2857, 0.1429, 0.1429, 0.1429)$$

In the third scenario, Transparency, Verifiability, and Traceability received twice the individual weight assigned to the technical dimensions:

$$W_{\text{institutional}} = (0.1250, 0.1250, 0.2500, 0.2500, 0.2500)$$

The values of the five dimensions were held constant and only the weights were modified. Comparing the main AHP specification with the three alternative scenarios made it possible to assess the stability of relative positions and identify trade-offs between technical performance and institutional attributes. This sensitivity analysis was used as a test of the internal robustness of the aggregation under different weighting structures, not as external validation of the MRV-EII.

As an additional robustness test, Accuracy (A) was excluded from the MRV-EII and the AHP weights of the four remaining dimensions were renormalized to sum to 1, resulting in C = 0.1035 and T = V = R = 0.2988. The purpose was to assess whether the comparative pattern depended on the dimension with the lowest direct comparability across functionally heterogeneous units. The test left the original scores for Consistency, Transparency, Verifiability, and Traceability unchanged, modifying only the composition of the index.

Illustrative jurisdictional application

An illustrative application of the framework and MRV-EII was conducted for Acre, Brazil, considering the System of Incentives for Environmental Services (SISA) and the ISA Carbon Program/Acre Carbon Standard.

The application considered a digital monitoring core comprising INPE, MapBiomas, and Global Forest Watch. For each dimension, the arithmetic mean of the scores for the three units was calculated. Equal weights across the units were adopted because the available data do not allow their relative contribution to the jurisdictional system to be objectively estimated.

The aggregate value was calculated using the main AHP weight vector and subjected to the same sensitivity scenarios used in the comparative analysis.

This application is demonstrative in nature. It does not constitute an audit, certification, or independent validation of the environmental integrity of SISA, the ISA Carbon Program/Acre Carbon Standard, or credits associated with the jurisdiction. Jurisdictional validation would require a specific assessment of MRV procedures, primary documentation, independent evaluation of the scores, and additional tests of index validity and reliability.

Results

Technical and operational characteristics of the units analyzed

The six units exhibited distinct functional configurations within the digital MRV ecosystem. Google Earth Engine operates primarily as a geospatial processing infrastructure; Global Forest Watch as a data-integration and dissemination platform; Planet Labs as a provider of high-resolution imagery; Sylvera as a carbon intelligence and assessment platform; MapBiomas as a collaborative land-use and land-cover mapping initiative; and INPE (PRODES/DETER) as an official public forest-monitoring system.

Reported accuracy in the selected applications ranged from 85% to 95%. Planet Labs and INPE showed ranges of 90–95%, Sylvera 88–94%, Google Earth Engine 85–92%, and Global Forest Watch and MapBiomas 85–90%. Spatial resolution ranged from 3–5 m for Planet Labs to approximately 30 m for Global Forest Watch, MapBiomas, and INPE, while update frequency ranged from daily to annual or near-real-time, depending on the unit and product analyzed (Table 1).

Table 1. Technical and operational characteristics of the units analyzed in the digital MRV ecosystem.

Analytical unit	Predominant function	Reported accuracy (%)	Spatial resolution	Update frequency	Relative cost	Analytical technology
Google Earth Engine	Cloud-based geospatial processing	85–92	10–30 m	Weekly/monthly	Low	ML
Global Forest Watch	Forest data integration and dissemination	85–90	30 m	Weekly	Low	Deep learning
Planet Labs	High-resolution imagery acquisition	90–95	3-5 m	Daily	High	CNN
Sylvera	Carbon intelligence and assessment	88–94	Variable	Periodic	High	Hybrid
MapBiomas	Land-use and land-cover mapping	85–90	30 m	Annual	Very low	ML
INPE (PRODES/DETER)	Official forest monitoring	90–95	30 m	Annual/near-real-time	Low	Hybrid

Source: Authors' compilation based on the technical and scientific documentation specified in the Methods and detailed in the documentary matrix.

Note: The ranges correspond to selected applications and do not represent universal properties of the units. The units perform different functions and are not interpreted as equivalent organizations.

The cost classification is qualitative and relative, based on publicly documented access and licensing conditions for the units, and does not constitute a standardized economic comparison.

The data show different combinations of resolution, frequency, and cost. Planet Labs exhibited the highest spatial resolution and daily frequency, accompanied by high relative cost. INPE combined reported accuracy of 90–95% with low relative cost and both annual and near-real-time monitoring products. MapBiomas showed the lowest update frequency among the units compared, associated with the lowest relative cost. No single profile simultaneously combined the highest spatial resolution, update frequency, and accuracy with the lowest relative cost.

MRV-related Environmental Integrity Index (MRV-EII)

MRV-EII values ranged from 0.65 to 0.99 across the six units (Table 2). The highest value was observed for INPE (0.99), followed by MapBiomas (0.95), Global Forest Watch (0.89), Google Earth Engine (0.81), Sylvera (0.73), and Planet Labs (0.65).

Table 2. MRV-EII applied to the units analyzed.

Analytical unit	A	C	T	V	R	MRV-EII-AHP
INPE	0.93	0.90	1.00	1.00	1.00	0.99
MapBiomas	0.88	0.80	1.00	0.90	1.00	0.95
Global Forest Watch	0.88	0.85	0.95	0.85	0.90	0.89
Google Earth Engine	0.89	0.85	0.80	0.75	0.85	0.81
Sylvera	0.91	0.75	0.60	0.85	0.70	0.73
Planet Labs	0.93	0.95	0.50	0.70	0.60	0.65

A: Accuracy; C: Consistency; T: Transparency; V: Verifiability; R: Traceability.

Source: Authors' compilation based on the criteria and documentary matrix described in the Methods and Supplementary Material S1, 2026.

The technical dimensions showed less dispersion than some institutional dimensions.

Accuracy scores ranged from 0.88 to 0.93 and Consistency from 0.75 to 0.95. By comparison, Transparency ranged from 0.50 to 1.00, Verifiability from 0.70 to 1.00, and Traceability from 0.60 to 1.00.

INPE and MapBiomas achieved the maximum scores for Transparency and Traceability. INPE also achieved the maximum score for Verifiability. Global Forest Watch scored between 0.85 and 0.95 across the three institutional dimensions. Google Earth Engine scored 0.80 for Transparency, 0.75 for Verifiability, and 0.85 for Traceability.

Sylvera and Planet Labs showed technical scores close to those of the other units but larger differences between their technical and institutional dimensions. For Planet Labs, for example, Accuracy and Consistency reached 0.93 and 0.95, whereas Transparency, Verifiability, and Traceability were 0.50, 0.70, and 0.60, respectively.

Sensitivity to the weighting structure

Changing the weights modified the magnitude of the MRV-EII but produced few changes in the relative ordering of the units (Table 3).

Table 3. MRV-EII under alternative weighting scenarios.

Analytical unit	AHP	Equal weights	Technical emphasis	Institutional emphasis
INPE	0.99	0.97	0.95	0.98
MapBiomas	0.95	0.92	0.89	0.94
Global Forest Watch	0.89	0.89	0.88	0.89
Google Earth Engine	0.81	0.83	0.84	0.82
Sylvera	0.73	0.76	0.78	0.75
Planet Labs	0.65	0.74	0.79	0.68

Source: Authors' compilation based on application of the MRV-EII to the four weighting scenarios defined in the Methods, 2026.

INPE, MapBiomas, Global Forest Watch, and Google Earth Engine retained the first four positions, respectively, under all four scenarios. The only reversal occurred between Sylvera and Planet Labs under the technical-emphasis scenario: Planet Labs increased from 0.65 under the AHP specification to 0.79, exceeding Sylvera's value of 0.78.

The range between the lowest and highest values across the four scenarios was 0.04 for INPE, 0.06 for MapBiomas, 0.01 for Global Forest Watch, 0.03 for Google Earth Engine, 0.05 for Sylvera, and 0.14 for Planet Labs.

Global Forest Watch therefore showed the lowest variation across scenarios, whereas Planet Labs showed the highest. For Planet Labs, the value increased from 0.65 under the AHP specification to 0.79 under technical emphasis and was 0.68 under institutional emphasis.

In the additional robustness test, excluding Accuracy did not alter the ordering of the six units. The recalculated values were 0.99 for INPE, 0.95 for MapBiomas, 0.89 for Global Forest Watch, 0.81 for Google Earth Engine, 0.72 for Sylvera, and 0.64 for Planet Labs. Thus, the main comparative pattern remained unchanged after removing the dimension with the lowest direct comparability across the units.

Illustrative jurisdictional application

The jurisdictional application considered INPE, MapBiomas, and Global Forest Watch as components of the digital monitoring core examined for Acre. The mean scores across the three units were approximately 0.90 for Accuracy, 0.85 for Consistency, 0.98 for Transparency, 0.92 for Verifiability, and 0.97 for Traceability.

Applying the MRV-EII produced similar values across the different weighting scenarios. The index remained between approximately 0.91 and 0.94. The equal-weight scenario yielded 0.92, the technical-emphasis scenario 0.91, and the institutional-emphasis scenario approximately 0.94.

The lowest relative score for the jurisdictional configuration was observed for Consistency (0.85), whereas Transparency (0.98) and Traceability (0.97) had the highest values. Variation in the MRV-EII across weighting scenarios remained below 0.04.

These values represent only the configuration composed of the three digital infrastructures included in the illustrative application and do not constitute an overall assessment of SISA, the ISA Carbon Program/Acre Carbon Standard, or the environmental integrity of credits associated with the jurisdiction.

Discussion

This study examined how digital and artificial intelligence capabilities interact with technical performance, institutional governance, and integrity in measurement, reporting, and verification (MRV) systems applied to REDD+, operationalizing this relationship through the MRV-EII. The findings support two conclusions. First, the units analyzed combine accuracy, spatial resolution, frequency, and cost in different ways, with no configuration dominating across all attributes. Second, Accuracy and Consistency scores showed less dispersion across units, whereas Transparency, Verifiability, and Traceability varied more strongly. Under the main weighting structure, this greater dispersion contributed more strongly to differences in aggregate scores. Greater technological capability therefore does not necessarily correspond to greater MRV integrity. This distinction is central to understanding digital MRV systems as simultaneously technological and institutional configurations.

The first conclusion is consistent with the recent evolution of forest monitoring. Remote sensing has expanded observational capacity over large spatial scales, as demonstrated by Hansen et al. (2013), while deep learning and high-resolution imagery have increased the capacity to detect forms of degradation that were previously difficult to identify. Dalagnol et al. (2023), for example, combined deep learning with Planet NICFI imagery to detect degradation associated with fire, logging, and roads in the Amazon. These advances are consistent with the high accuracy and update frequency observed in some of the configurations analyzed.

The findings are also consistent with the literature questioning the equivalence between algorithmic performance and MRV quality. Lines et al. (2022) highlight limitations associated with data heterogeneity, the absence of common benchmarks, and the difficulty of comparing algorithms across contexts. Bos et al. (2019) show that high aggregate accuracy can coexist with substantial uncertainties and that combining multiple sources requires explicit accuracy assessment. The absence of a configuration simultaneously dominant in accuracy, resolution, frequency, and cost therefore suggests that digitalization shifts, but does not eliminate, trade-offs in forest monitoring.

This interpretation requires caution. The performance measures were obtained from different applications and documents; accordingly, the findings do not establish a causal effect of AI on accuracy, monitoring frequency, or scalability in MRV systems. Rather, they show that these capabilities are present in the digital configurations examined and can be enabled by cloud processing, integration of multiple data sources, and algorithmic methods. The contribution of this study lies less in claiming the technological superiority of AI than in examining the conditions under which technical capability can produce credible environmental information.

In this sense, the findings build on a pattern already identified in the literature on MRV capacity. Romijn et al. (2012) documented important differences among countries in the implementation of national forest monitoring systems for REDD+. Ochieng et al. (2016) advanced this analysis by showing that relatively high technical capacity can coexist with limitations in administrative capacity and good governance. Yang et al. (2025) confirm that REDD+ readiness involves capacities that extend beyond the availability of observation technologies. The present findings extend this asymmetry to the context of digital MRV: units with similar technical performance exhibited larger differences in transparency, verifiability, and traceability. Digitalization therefore expands measurement capacity but does not eliminate the need for institutional capacity.

This interpretation also converges with the notion of carbon accountability proposed by

Gupta et al. (2012). By challenging the representation of MRV as a strictly technical activity, the authors show that measuring carbon simultaneously involves knowledge production, standardization, and the accountability of those who produce and validate information. The present study extends this argument to the digital context: as imagery providers, algorithms, computational infrastructures, integration platforms, and public institutions increasingly share in the production of environmental evidence, MRV governance encompasses not only what is measured but also how an estimate was produced, documented, and made verifiable. This provides the basis for interpreting digital MRV as a sociotechnical infrastructure.

The study further extends this literature by shifting the analytical focus from aggregate national capacity to the sociotechnical infrastructures that produce MRV information. Digitalization distributes the production of environmental evidence across imagery providers, computational infrastructures, algorithms, integration platforms, public institutions, and validation systems. In this environment, data availability or computational capacity does not ensure that third parties can understand, reproduce, or verify a given estimate.

This distinction is reflected in the MRV-EII results. Accuracy scores were concentrated within a relatively narrow range, whereas Transparency, Verifiability, and Traceability showed greater dispersion. Units with similar technical performance therefore achieved different aggregate values once the institutional dimensions were incorporated. This does not demonstrate the intrinsic superiority of public, commercial, or collaborative platforms; rather, it shows that technical sophistication and institutional openness are distinct attributes.

This distinction is consistent with the literature on algorithmic governance. Kroll et al. (2017) argue that automated systems require accountability mechanisms that make it possible to assess how results are produced. Similarly, Barredo Arrieta et al. (2020) show that high predictive performance does not eliminate problems of explainability and scrutiny. In MRV, therefore, technically robust estimates can coexist with different levels of access to the data, procedures, versions, and criteria required for verification.

The sensitivity analysis reinforces this interpretation while delimiting the scope of the MRV-EII. INPE, MapBiomas, Global Forest Watch, and Google Earth Engine retained their relative positions across the four scenarios, whereas units with greater asymmetry between technical and institutional dimensions varied more strongly. Planet Labs, for example, increased its MRV-EII when greater weight was assigned to the technical dimensions. The ranking therefore depends on the normative assumptions embedded in the index, as expected for composite indicators in which selection, weighting, and aggregation influence results (OECD/European Union/EC-JRC, 2008).

The MRV-EII should consequently be interpreted as a diagnostic instrument rather than a universal ranking. The main weighting structure makes explicit the theoretical proposition that transparency, verifiability, and traceability are relevant to MRV integrity, while the alternative scenarios test the sensitivity of that proposition. The observed relative stability indicates internal robustness to weighting, not external validation. In addition, excluding Accuracy fully preserved the ordering of the units, indicating that the main comparative pattern does not depend on the dimension with the lowest direct comparability.

The concept of integrity must also be delimited. Schneider and La Hoz Theuer (2019) show that the integrity of international carbon market mechanisms involves unit quality, accounting rules, mitigation-target ambition, and market incentives. West et al. (2023) demonstrate that baseline and measurement problems can compromise forest-conservation credits. The MRV-EII does not replace these approaches: additionality, permanence, leakage, baselines, and double counting are not directly measured. Its contribution is to operationalize integrity related to the production, documentation, verification, and tracing of MRV information.

The framework thereby bridges two strands of the current literature. The technological literature emphasizes observation, classification, resolution, and accuracy (Hansen et al., 2013; Lines et al., 2022; Dalagnol et al., 2023), whereas the carbon-market literature emphasizes accounting, credit quality, additionality, and climate effectiveness (Schneider and La Hoz Theuer, 2019; West et al., 2023). The sociotechnical framework connects these levels by treating MRV as the infrastructure through which technical outputs become institutionally usable evidence.

The illustrative application to Acre should be interpreted within this analytical scope. The configuration composed of INPE, MapBiomas, and Global Forest Watch achieved high scores particularly for Transparency, Verifiability, and Traceability and showed little variation across scenarios. This demonstrates the operationalization of the MRV-EII in a composite configuration but does not allow a specific level of integrity to be attributed to SISA, the ISA Carbon Program/Acre Carbon Standard, or credits associated with the jurisdiction. Such an assessment would require a specific examination of institutional procedures, the data sources actually used, accounting rules, and validation arrangements.

Nevertheless, the application highlights an implication for forest policy. Different monitoring sources can be complementary (Bos et al., 2019), and REDD+ allows existing systems and subnational monitoring to be combined within national monitoring systems (UNFCCC, 2013a). Public decision-making therefore concerns not only which technology to use, but also how different components are connected, documented, and subjected to common validation. Requirements for methodological documentation, provenance, versioning, interoperability, reproducibility, and independent verification can complement criteria such as accuracy, resolution, and frequency. Proprietary systems are therefore not inherently incompatible with MRV integrity; however, intellectual-property protection must be reconciled with a level of auditability appropriate to the regulatory or financial use of their outputs.

The main theoretical contribution can be synthesized as a sociotechnical integrity proposition: increases in technological performance do not necessarily produce equivalent increases in MRV integrity; the conversion of technical capability into credible environmental evidence is mediated by transparency, verifiability, and traceability, which jointly create conditions for accountability. The MRV-EII operationalizes this proposition by making observable the relationship between technical performance and institutional conditions of validation. The argument is not that institutions are always more important than technology, but that their interaction can be made explicit, compared, and subjected to alternative weighting structures.

This interpretation repositions algorithmic governance within REDD+. As algorithms, commercial data, and computational infrastructures become involved in estimates used by governments and markets, governing MRV also entails governing the processes that produce those results. Methodological transparency, versioning, auditability, and the assignment of responsibilities become components of the institutional infrastructure of forest carbon markets.

The study has five main limitations: the use of secondary evidence and non-standardized applications across units; functional heterogeneity among the units; ordinal scoring of several MRV-EII dimensions; theoretical-normative AHP weights without independent expert elicitation; and the demonstrative nature of the Acre application. Future studies should incorporate independent evaluators and inter-rater agreement, compare theoretical and expert-derived weights, test the MRV-EII across different REDD+ jurisdictions, and incorporate uncertainty into the scores. They could also assess whether transparency, traceability, and verifiability are associated with external outcomes such as audits, technical reviews, verification costs, and stakeholder confidence.

Taken together, the findings indicate that digitalization does not eliminate the institutional problem of integrity; it transforms it. Digital MRV systems can be understood as sociotechnical infrastructures of forest governance: technology expands measurement capacity, while institutions define the conditions under which that capacity is converted into credible evidence for public policy and carbon markets.

Conclusions

This study examined how digital and artificial intelligence capabilities interact with technical performance, institutional governance, and integrity in measurement, reporting, and verification (MRV) systems applied to REDD+. The findings show that greater technological capability does not necessarily imply greater MRV integrity. The units analyzed exhibited relatively similar technical performance, whereas transparency, verifiability, and traceability showed greater dispersion and contributed more strongly to differences in aggregate scores under the weighting structure adopted.

The main theoretical advance lies in understanding MRV integrity as the outcome of a sociotechnical relationship. Technology expands monitoring, processing, and measurement capacity, while institutional mechanisms mediate the conditions under which results can be understood, verified, and reconstructed. This relationship is summarized in the sociotechnical integrity proposition: increases in technological performance do not necessarily produce equivalent increases in integrity; the conversion of technical capability into credible environmental evidence is mediated by transparency, verifiability, and traceability, which jointly create conditions for accountability.

The MRV-EII operationalizes this proposition by integrating technical and institutional dimensions within a comparative framework. The sensitivity analysis showed that the index responds to weighting assumptions while maintaining broad stability in the relative ordering of the units analyzed. The MRV-EII should therefore be understood as a diagnostic instrument rather than a universal ranking or a complete measure of the integrity of REDD+ programs or carbon credits. The illustrative application to Acre demonstrated its operationalization in a jurisdictional context without constituting validation of SISA or the ISA Carbon Program/Acre Carbon Standard.

The expansion of digital MRV thus shifts the integrity problem from a predominantly technical issue to one that is simultaneously technological and institutional. MRV systems capable of supporting credible forest policies and carbon markets depend not only on better algorithms and data, but also on institutional conditions that make their estimates transparent, verifiable, and traceable.

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