Digital MRV for carbon credits: integrating AI, satellites, IoT and blockchain for reliable climate claims

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Abstract

Digital measurement, reporting and verification (dMRV) is increasingly proposed as the operating system for carbon markets. It combines earth-observation data, field and device sensors, machine-learning models, digital data infrastructure and distributed ledgers to make climate claims more frequent, traceable and auditable. Yet digitization does not by itself establish additionality, permanence, net greenhouse-gas benefit or a valid baseline. This review develops a reliability-first assessment of four dMRV building blocks satellites, Internet-of-Things (IoT) sensors, artificial intelligence (AI) and blockchain and explains how they should be integrated with a crediting methodology, independent assurance and registry controls. The paper synthesizes technology roles across forestry, agriculture, clean cooking, renewable energy, waste, industrial energy efficiency and carbon dioxide removal. It proposes an end-to-end assurance loop, a net-credit data model and a quantitative capability scorecard. The analysis shows that satellites are strongest for broad spatial coverage and disturbance detection; IoT is strongest for high-frequency operational evidence; AI enables prediction, fusion and anomaly screening but imports model and training-data uncertainty; blockchain strengthens tamper-evident provenance and serialization but cannot validate the physical truth of an input. A credible digital credit therefore rests on triangulation: independent sources must agree within pre-defined uncertainty thresholds, exceptions must be reviewable, and the final issuance quantity must be calculated conservatively. The review concludes with a practical architecture and governance checklist for developers, standards, verifiers, registries and buyers.

Keywords: digital MRV; carbon credits; remote sensing; artificial intelligence; Internet of Things; blockchain; carbon-market integrity; verification; satellite monitoring

1. Introduction

Carbon crediting converts a measured change relative to a baseline into a tradable, uniquely identified claim. The traditional pathway is often document-intensive: field teams collect evidence, project proponents prepare spreadsheets and monitoring reports, a validation/verification body reviews the evidence, and a registry issue serialized unit. This workflow is necessary but expensive and intermittently observed. It can leave large time gaps between a field event, a detected reversal and a market response. Digital MRV seeks to improve this process through more frequent, machine-readable and traceable evidence [1–4].

The promise is substantial, particularly for distributed projects where manual monitoring is costly: forests and farms, small energy devices, methane management, clean cooking, wastewater treatment and emerging CDR. The risk is equally substantial. A satellite classification may identify canopy change but cannot directly observe soil carbon; a smart meter can show device operation but not necessarily the counterfactual fuel displaced; a blockchain ledger can preserve a hash but cannot prove that the original sensor was calibrated. Crediting must therefore preserve the logic of the methodology and treat digital tools as evidence instruments rather than automatic truth machines.

This paper answers four questions: what can each digital component measure; how should components be combined with methodology rules and independent verification; what numerical indicators should be monitored to judge system reliability; and which governance controls protect a credit from false data, over-confident models and double use?

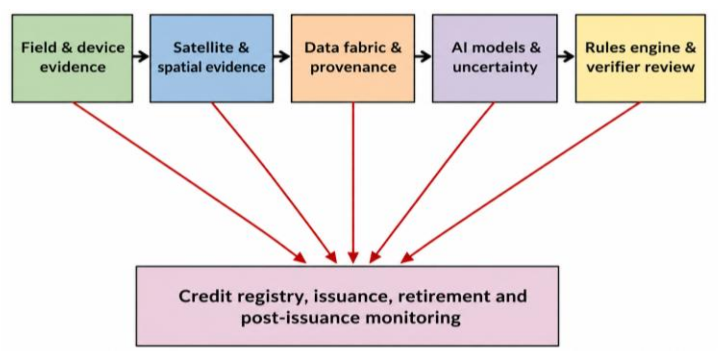

Figure 1. Digital MRV architecture linking physical evidence, data provenance, AI-assisted quantification, assurance and registry functions

A reliable digital MRV system depends on the coordinated use of multiple evidence sources instead of relying on a single technology or data stream. Figure 1 illustrates the overall digital MRV architecture by showing how physical observations, data management, AI-supported analysis, verification, and registry functions work together to support credible carbon credit issuance.

2. Scope, review method and definitions

The review synthesizes official carbon-market guidance, standards documents, digital-MRV pilots, remote-sensing and data-governance literature. It does not treat vendor marketing numbers as performance evidence. Where a numerical score is presented, it is an explicit analytical tool devised for comparison, not a measured market average. This matters because reported cost and accuracy claims use incompatible baselines, project scales and verification scopes.

Table 1. Core definitions and the common category errors they are designed to prevent.

Term	Meaning in this review	Not sufficient on its own
Measurement	Observation of a physical variable or activity: energy, area, biomass proxy, gas flow, cooking event.	A measured activity is not automatically a GHG outcome.
Reporting	Structured transmission of evidence, calculations and assumptions.	A digital report does not establish accuracy.
Verification	Independent assessment against a methodology and assurance standard.	Automation does not remove verifier accountability.
dMRV	Digitally enabled MRV using machine-readable, time-stamped evidence and automated controls.	dMRV is not synonymous with blockchain or AI.
Credit	Serialized unit issued under a registry rule after verification.	A token or dashboard counter is not necessarily an issued credit.

Clear definitions help distinguish technical terms that are often used interchangeably, reducing confusion during project implementation and verification. Table 1 summarizes the key concepts adopted in this review while highlighting the common misconceptions that should be avoided when interpreting digital MRV systems.

3. Four building blocks of dMRV

3.1 Satellite and remote-sensing evidence

Earth observation offers repeated, wide-area observation of land cover, vegetation condition, thermal anomalies, water extent, infrastructure and atmospheric constituents. Open optical imagery such as Sentinel-2 provides 10 m spatial resolution for selected bands, while Landsat provides 30 m multispectral observation; radar can supply cloud-penetrating structural information. These data are valuable for project-boundary review, stratification, disturbance alerts, sampling design and monitoring of areas too large for only ground plots [5–7].

Remote sensing is strongest when the measured variable is observable or closely linked to an observable proxy. Forest cover change and burn scars may be observable; biomass and soil carbon are usually modelled from proxy variables and calibration plots. The appropriate claim is therefore “model-assisted carbon estimate, calibrated and validated with field data”, not “satellite-measured carbon”. Methodologies such as Verra’s ARR approach explicitly combine remotely sensed vegetative-cover change with plot-based sampling [8].

3.2 IoT and device-level evidence

IoT systems include smart meters, fuel-flow sensors, temperature and pressure sensors, gas analyzers, GPS trackers, weighbridges, telemetric controllers and mobile applications. Their advantage is event-level granularity. In a biogas project, a flow meter can record gas delivery; in a clean-cooking programme, a metered device can record usage; in an industrial CDR system, sensors can record CO_2 flow, energy use, alkalinity or operating conditions. The data become credible only when the device identity, calibration, time synchronization, connectivity status, tamper response and missing-data rules are defined.

IoT evidence must be designed around the methodological equation. A project should collect the minimum variables necessary to calculate the credit plus the variables needed to detect failure. Collecting abundant telemetry without a link to baseline, emission factor, leakage or permanence does not improve the credit. Conversely, an elegant equation with no reliable activity data cannot support issuance.

3.3 AI and data fusion

AI supports image classification, biomass modelling, methane-plume detection, anomaly detection, device-use classification, document consistency checks, sampling optimisation and evidence fusion. Its greatest value is not replacing a methodology but making the uncertainty visible and decision-relevant. A model should state its target variable, training data, geographic and temporal applicability, validation design, error metric, confidence interval, failure modes and rule for human review.

AI models can generalize poorly when a project moves to a new geography, sensor, season, crop system or device type. Model drift can be caused by changing land management, climate extremes, instrument upgrades or altered user behavior. The appropriate control is periodic recalibration against independent ground truth, held-out validation data, out-of-distribution detection and conservative deductions when model uncertainty grows.

3.4 Blockchain and data provenance

Blockchain can provide tamper-evident timestamping, shared transaction visibility, programmable controls and unique tokenization. Its legitimate role is evidence provenance and lifecycle control: anchoring hashes of data files, recording permissions, linking verifications to serial numbers and preventing unauthorized transfer of a retired unit. It is not a measurement technology. “Garbage in, immutable garbage out” remains the essential limitation: blockchain cannot independently establish the correctness of a sensor value, an AI output or a baseline assumption.

A sensible architecture therefore stores high-volume raw data and personal or commercially sensitive data off-chain, retains access controls, and commits hashes or signed evidence manifests to a ledger or registry interface. Carbon-credit registries remain the authoritative source of issuance and retirement unless a standard expressly delegates those functions.

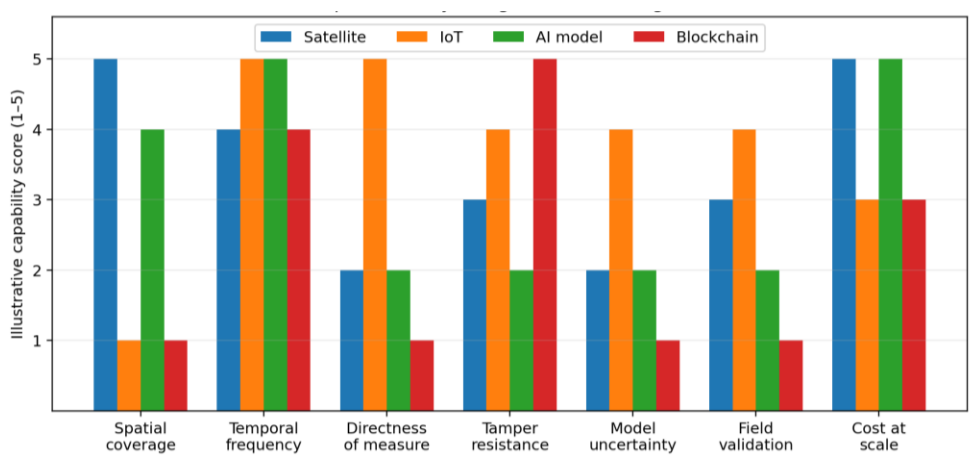

Figure 2. Comparative capability scorecard of satellite, IoT, AI, and blockchain technologies across key digital MRV functions.

Figure 2 demonstrates why a single "digital-MRV platform" is rarely enough. Satellite data provide broad coverage but are generally indirect for carbon; IoT provides direct operational evidence but limited spatial reach; AI can integrate streams but may introduce model risk; blockchain protects provenance but does not observe the physical world. A robust system combines them according to the project's main uncertainty.

Table 2. Evidence requirements, verification data, limitations, and independent validation for major digital MRV components

Component	**Strongest use**	**Key numerical evidence to retain**	**Primary limitation**	**Independent check**
Satellite / GIS	Area, land-cover, disturbance, stratification	Image date, sensor, spatial resolution, cloud mask, classification confidence	Indirect carbon inference; cloud, shadows and mixed pixels	Field plots, radar/optical comparison, third-party imagery
IoT	Usage, flows, energy, temperature, gas concentration	Device ID, calibration date, sampling frequency, uptime, data gaps	Sensor drift, tampering, connectivity gaps	Bench test, redundant sensor, random site audit
AI	Prediction, classification, anomaly detection, data fusion	Training period, held-out error, bias by stratum, confidence interval	Drift and poor transferability	Independent validation set and human exception review
Blockchain	Evidence hashes,	Hash, signature, timestamp, access	Cannot validate	Verifier

	permissions, serialisation, audit trail	log, registry serial number	physical data	review of original signed source files

The value of digital evidence depends not only on the information collected but also on its quality, traceability, and independent validation. Table 2 outlines the primary role of each digital MRV component together with the numerical evidence, limitations, and verification checks required to strengthen confidence in carbon credit assessments.

4. The end-to-end dMRV assurance loop

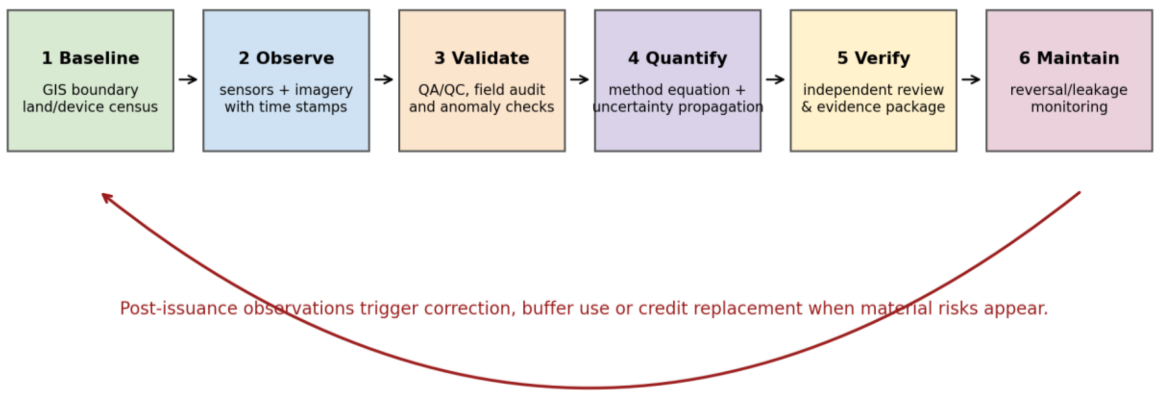

Figure 3. Closed-loop assurance process from baseline to post-issuance monitoring and corrective action

A dMRV system should be governed as an assurance loop (Figure 3). The baseline is a documented counterfactual and project boundary. Observation then records the relevant activity and environmental state. Validation checks completeness, plausibility, geospatial consistency, calibration and anomalous patterns. Quantification applies the approved methodology and propagates uncertainty. Independent verification assesses the evidence package and the controls. Finally, post-issuance monitoring detects reversal or deviation and triggers correction, buffer use or replacement.

The system should define "machine stops": conditions under which data may be collected but credits cannot be auto-quantified. Examples are sensor calibration overdue, image cloud coverage above the defined threshold, missing coordinates, model confidence below threshold, material boundary changes, outage longer than an approved interval, or a mismatch between physical-meter totals and reported activity. The correct response is not interpolation by default; it is the methodology-defined treatment, conservative substitution or manual investigation.

4.1 Quantification and uncertainty propagation

For a project period t, a generic credit quantity can be written as $C_t = (ER_t - L_t - U_t - R_t) \times (1 - B_t)$, where ER is calculated emission reduction or removal relative to the baseline, L is leakage, U is the uncertainty deduction, R is a reversal or non-permanence adjustment and B is the buffer contribution. Digital systems make each term more traceable but do not eliminate the need to define it under the methodology. The evidence package should make it possible to reproduce C_t from raw observations, data transformations, model version and approved parameter values.

A practical dMRV confidence dashboard should show at least: data completeness (% of expected records received); calibration compliance (% of active devices within calibration); model coverage (% of project area or events within model applicability); verification exceptions (count and severity); and uncertainty deduction (tCO_2e and percentage of gross result). These indicators describe the reliability of the measurement chain rather than the size of the project.

Table 3. Reliability metrics and decision indicators for digital MRV operational monitoring

Metric	**Formula / field**	**Decision use**	**Illustrative escalation threshold**
Data completeness	received valid records ÷ expected records × 100	Detects missing activity evidence	Below methodology-defined minimum: hold quantification
Calibration compliance	in-calibration devices ÷ active devices × 100	Tests measurement validity	Any critical device overdue: manual review
Spatial coverage	valid observed area ÷ credited area × 100	Tests remote-sensing representativeness	Unobserved strata require sampling or deduction
Model applicability	observations inside training/validation domain ÷ total	Detects extrapolation	Low coverage: do not extend model claim
Exception rate	flagged records ÷ total records × 100	Monitors anomalies and fraud risk	Rising trend: investigate root cause
Uncertainty deduction	conservative deduction ÷ gross claim × 100	Limits over-crediting	Increase when error or transfer risk rises

Operational indicators provide an objective way to evaluate whether the monitoring system is producing reliable and verifiable evidence over time. Table 3 presents the core reliability metrics and their decision-making roles, allowing project developers and verifiers to identify situations that require corrective action before credit issuance.

5. Applications by project type

5.1 Nature-based carbon projects

In afforestation, reforestation and improved forest management, dMRV can map project boundaries, stratify vegetation, identify deforestation or fire, guide plot allocation, estimate biomass models and monitor survival. The fundamental constraints are additionality, baseline setting, biomass-model error, leakage and permanence. Digital tools can improve detection of disturbance and sampling efficiency; they cannot infer legal rights, community consent or the counterfactual land-use trajectory solely from imagery.

Agricultural soil-carbon projects require an even more cautious architecture. Remote sensing can characterize crop cover and practice proxies, while farm apps can capture management data and soil sampling provides calibration. The carbon stock itself is spatially variable and changes slowly relative to measurement noise. Verra's digital soil-mapping work explicitly requires calibration, validation and uncertainty deductions for spatially explicit estimates [9].

5.2 Clean cooking and distributed energy

Metered clean-cooking and distributed-energy projects are well suited to IoT because the credited intervention is device operation or measured energy service. A credible design must nevertheless validate device identity, household assignment, fuel stacking, usage classification, grid or fuel baseline, uptime and adoption persistence. Digital logs should be reconciled with periodic surveys and physical inspections to ensure that a recorded event represents the creditable service assumed by the methodology.

5.3 Waste, methane and industrial projects

Landfill gas, biogas, wastewater methane, flaring and industrial efficiency projects can combine continuous process meters with periodic gas sampling, supervisory-control logs and anomaly detection. The most important risks are metering bias, bypass operation, assumed destruction efficiency, leak points outside the instrumented boundary and double counting of renewable-energy attributes. Here dMRV can materially improve high-frequency reconciliation between fuel input, gas generation, capture, destruction and energy output.

5.4 Carbon dioxide removal

CDR adds explicit durability, lifecycle and reversal requirements. DACCS and BECCS systems can use flow meters, energy data, CO_2 composition, compression logs and storage monitoring. Biochar requires feedstock chain-of-custody, batch chemistry and end-use evidence. Weathering and ocean alkalinity require distributed geochemical measurements, tracers, models and ecological safeguards. Digital systems improve data availability but must not reduce a net-removal claim to a device reading; gross captured or dosed material must be reconciled with lifecycle emissions, storage fate and uncertainty.

Table 4. Digital MRV data architecture and supporting evidence requirements across major carbon project categories.

Project type	Digital data bundle	Main model/claim risk	Non-digital evidence that remains essential
ARR / forest	Sentinel/Landsat/radar, GPS plots, mobile forms, fire alerts	Biomass transfer error; baseline and leakage	Plot inventory, land rights, community process, field audit
Soil carbon	Farm records, imagery, weather,	Small signal vs soil variability;	Laboratory QA/QC, stratified

	soil samples, AI map	practice attribution	sampling, agronomic evidence
Clean cooking	Device telemetry, app enrolment, surveys, GPS	Fuel stacking; device use ≠ displaced fuel	Household verification, baseline study, survey checks
Waste / methane	Flow, CH_4 %, pressure, flare status, SCADA	Meter bias, bypass and destruction assumptions	Calibration, gas sampling, engineering audit
CDR	Mass/energy meters, chemistry, logistics, storage records	Gross activity mistaken for net durable removal	LCA, storage monitoring, third-party technical review

Digital technologies enhance monitoring efficiency, but they must always be supported by project-specific technical and field evidence to maintain the credibility of climate claims. Table 4 compares the recommended data architecture for different project categories while identifying the principal risks and the essential non-digital evidence required for each application.

6. Governance, cybersecurity and ethics

Digitalisation concentrates risk as well as efficiency. A compromise in a data pipeline can affect thousands of records; a flawed model can systematically overstate an entire portfolio; a public ledger can expose sensitive household, farm or indigenous-land information. Governance therefore needs clear data ownership, consent, access control, retention rules, cyber incident response, independent audit rights and redress mechanisms. The relevant question is not only "is the data immutable?" but also "who generated it, who can see it, who can correct an error, and how is the correction disclosed?"

AI governance should include model cards, data sheets, version control, reproducible code or locked executable environments, bias testing by project stratum and a documented human-in-the-loop process. Blockchain governance should include identity management, permission architecture, key recovery, smart-contract audit, off-chain storage controls and a tested linkage to the authoritative registry. A registry serial number remains more important to claim integrity than a speculative token price.

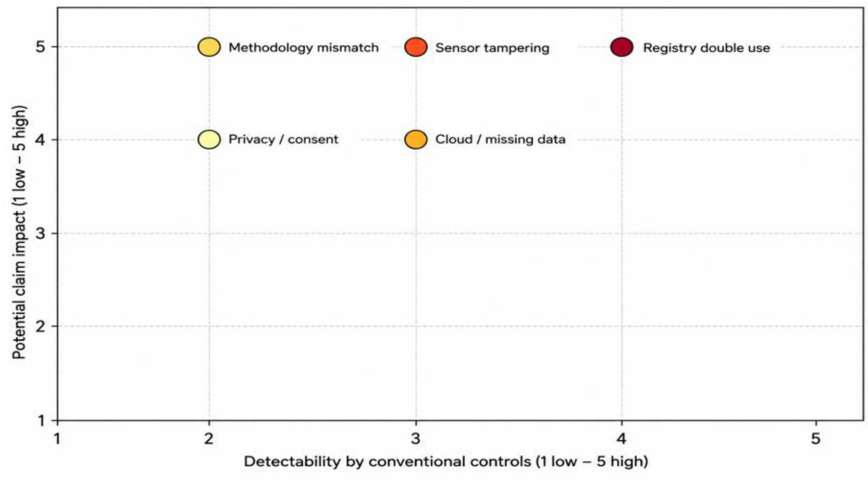

Figure 4. Risk matrix illustrating key governance and operational risks in a digital MRV programme

Figure 4 highlights a useful governance principle: the most material risks are not always the easiest to detect. Boundary fraud, methodology mismatch and model drift can create systematic over-crediting even when the data system is technically secure. Risk controls must therefore cover the scientific method, the instrument, the data pipeline, the model, the verifier and the registry not merely the ledger.

7. Quantitative analytical framework

To make digital-MRV choices transparent, this review proposes a Digital MRV Assurance Index (DAI). It is a comparative procurement tool, not a crediting methodology. Score each dimension from 0 to 5 and use explicit weights: physical measurement quality (0.20), data completeness and provenance (0.15), model validation and uncertainty (0.20), independent verification access (0.15), baseline and boundary integrity (0.15), reversal/leakage monitoring (0.10) and safeguards/privacy (0.05). DAI = $\Sigma w_i s_i / 5 \times 100$. The index should never be used to increase issued credits; it should determine whether the system is sufficiently reliable for the intended monitoring frequency and risk profile.

Table 5. Digital MRV Assurance Index (DAI) scoring framework for evaluating system reliability

Dimension	Weight	What earns a high score	What should lower the score
Physical measurement quality	0.2	Traceable calibrated instruments or independently validated field observations	Uncalibrated devices, proxy without calibration, unknown coverage
Data provenance and completeness	0.15	Signed records, lineage, high valid-record coverage, exception logs	Editable files without lineage, unresolved gaps
Model validation and uncertainty	0.2	Held-out validation, strata-specific error, recalibration plan	Opaque model, no independent test set, extrapolation
Independent verification access	0.15	Raw data and code/model-version access for verifier	Dashboard-only review or proprietary black box

Baseline and boundary integrity	0.15	Clear counterfactual, geospatial boundary and change control	Static baseline despite material context change
Reversal/leakage monitoring	0.1	Continuous alerts, response plan and buffer/replacement rules	No post-issuance monitoring
Safeguards and privacy	0.05	Consent, minimization, access controls and grievance channel	Sensitive data exposed or no redress process

Assessing the overall quality of a digital MRV system requires consideration of several technical, operational, and governance factors rather than focusing on a single performance indicator. Table 5 introduces the Digital MRV Assurance Index by defining the evaluation dimensions, their respective weights, and the criteria used to distinguish stronger and weaker system designs.

8. Strategic insights and recommendations

- Start with the carbon equation, not the technology. Select data only after defining the baseline, parameters, uncertainty and permanence terms.
- Use triangulation. At least two independent evidence types should test the most material project risk for example, satellite alerts plus plot audits, or IoT logs plus household surveys.
- Treat AI as a quantified model, not a narrative. Require a validation set, uncertainty interval, drift-monitoring plan and human escalation rule.
- Use blockchain narrowly and well. Anchor evidence provenance and serialization, but keep raw sensitive data access-controlled and defer issuance/retirement to the authoritative registry.
- Design for verifier reproducibility. A qualified verifier should be able to trace any issued tonne back to its source observations, transformations, model version and approval decision.
- Keep post-issuance monitoring active. A crediting period is not a reason to stop observing reversals, leakage, sensor failure or a material change in the baseline.

For standards, the immediate priority is pathway-specific digital-MRV guidance that defines acceptable data quality, model validation, uncertainty deductions, cybersecurity, privacy and verification access. Gold Standard’s dMRV pilot programme, operating through October 2026, and Verra’s work on remote sensing and digital soil mapping indicate a shift from generic enthusiasm toward controlled testing of methodology-compatible systems [10–12]. For developers, the practical goal should be a verifiable evidence package, not a visually impressive dashboard. For buyers, the priority is disclosure: whether the claimed quantity was directly measured, modelled, or estimated from default factors; how much was deducted for uncertainty; and how long the claim will remain valid.

9. Conclusion

Digital MRV can make carbon crediting more timely, traceable and scalable, particularly where projects are spatially dispersed or operationally continuous. Its core value is not automation alone but the ability to preserve an auditable chain from physical evidence to a conservative credit quantity. Satellites, IoT, AI and blockchain serve different functions and must be combined rather than treated as substitutes. Satellites strengthen coverage and disturbance monitoring; IoT strengthens direct activity evidence; AI strengthens fusion and anomaly detection while requiring stringent validation; blockchain strengthens provenance and transaction control while remaining unable to validate the physical world.

The governing principle is simple: a digital system becomes credible only when it makes over-crediting harder to commit, easier to detect and possible to correct. That requires methodology-first design, data-quality controls, uncertainty propagation, independent review, privacy safeguards and post-issuance monitoring. Carbon markets should reward these verified outcomes, not the presence of a digital label.

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