

A Block chain-Enabled Monitoring, Reporting, and Verification Framework for Blue Carbon Projects: A Critical System Evaluation

Poral Nagaraj¹, Ramesh B E², Amrutha C M³, Vaishnavi R⁴, and Vidyashree R⁵

1,2 Associate Professor, Department of Computer Science and Engineering, SJM Institute of Technology (SJMIT), Chitradurga, Karnataka, India

3,4,5 Seventh Semester, Department of Computer Science and Engineering, SJM Institute of Technology (SJMIT), Chitradurga, Karnataka, India

Abstract — Blue carbon monitoring, reporting, and verification (MRV) systems must connect field-level ecosystem observations to auditable carbon-accounting records. This paper describes and critically evaluates a prototype BlueCarbon Registry that integrates project registration, Sentinel-2 satellite analysis, Normalized Difference Vegetation Index (NDVI) computation, automated carbon estimation, MRV report generation, human verification, and blockchain registration. The prototype uses Sentinel-2 Level-2A imagery and the red (Band 04, B04) and near-infrared (Band 08, B08) bands at 10-meter resolution. In a case study, a 100-hectare mangrove project in Karnataka, India, produced a mean NDVI of 0.133, classified by the system as poor vegetation status, an estimated biomass of 407.98, and an estimated carbon dioxide equivalent (CO_{2e}) value of 703.09 tonnes of CO₂ equivalent (tCO_{2e}), which the system also recorded as the carbon-credit value. These results show that the platform can move a project through a complete digital workflow, but they do not constitute an independently certified carbon-removal claim. The implementation does not document the biomass-to-CO_{2e} conversion equation, calibration data, field validation, uncertainty quantification, or a baseline for measuring change over time. We identify five requirements a production system must satisfy before its carbon output can be trusted: reproducible geospatial processing, a documented carbon-conversion methodology, temporal baselines, field validation, and a fully auditable blockchain trail.

Keywords — blue carbon; mangrove ecosystems; remote sensing; Sentinel-2; Normalized Difference Vegetation Index (NDVI); monitoring, reporting and verification (MRV); blockchain; carbon registry.

I. INTRODUCTION

Mangroves and other blue carbon ecosystems store large amounts of carbon, but their climate value cannot be established from project registration alone. A credible carbon project needs a repeatable chain that links field observations, calculations, review decisions, and registry records. This paper presents a prototype system, the BlueCarbon Registry, that connects four layers: project registration, satellite-based vegetation analysis, MRV report generation with human verification, and blockchain registration.

Interest in blue carbon has grown because mangrove, sea grass, and tidal-marsh ecosystems sequester carbon at rates that can exceed those of many terrestrial forests, while also protecting coastlines and supporting local livelihoods. Bringing these ecosystems into carbon markets requires MRV procedures that are transparent enough for an external party to trust the reported numbers. Existing blue carbon MRV workflows are frequently split across separate tools for spatial analysis, spread sheet-based accounting, and manual documentation, which makes it difficult to trace a final reported figure back to the observation that produced it. The prototype examined in this paper responds to that operational gap by placing registration, analysis, reporting, verification, and registry functions inside a single connected application.

The contribution of this work is architectural rather than methodological. The platform links project creation to satellite image analysis, converts the resulting vegetation indicator into

an MRV record, routes that record through a verification step, and then supports blockchain registration. This sequence makes the digital workflow traceable, but it does not by itself validate the scientific method used to estimate biomass or carbon dioxide equivalent. The remainder of this paper describes the system architecture (Section II), reviews related work (Section III), presents the remote-sensing methodology and a case study (Section IV), reports the results obtained (Section V), evaluates the prototype along four evaluation dimensions and discusses what it demonstrates (Sections VI and VII), examines its limitations (Section VIII), and outlines requirements for production deployment, data availability, and directions for future work (Sections IX through XI).

II. SYSTEM ARCHITECTURE

Fig. 1 shows the five-stage pipeline implemented by the prototype.

1) Project registration: stores the project name, owner, location, area, project type, description, and supporting imagery. A project becomes available to the satellite-analysis module once it is approved, which establishes project identity before any analytical result exists.

2) Satellite analysis: accepts red and near-infrared inputs and computes NDVI at the pixel and project level. The interface exposes minimum, maximum, and mean NDVI together with a vegetation classification.

3) MRV report generation: converts the project and analysis records into a structured report containing project metadata, analysis information, vegetation status, biomass output, carbon / CO₂ output, and verification status.

4) Verification: presents completed projects awaiting review and provides verifier actions to approve or reject a result, creating a control point between analysis and permanent registration.

5) Blockchain registration: connects the registry workflow to a blockchain transaction through MetaMask once verification is complete.

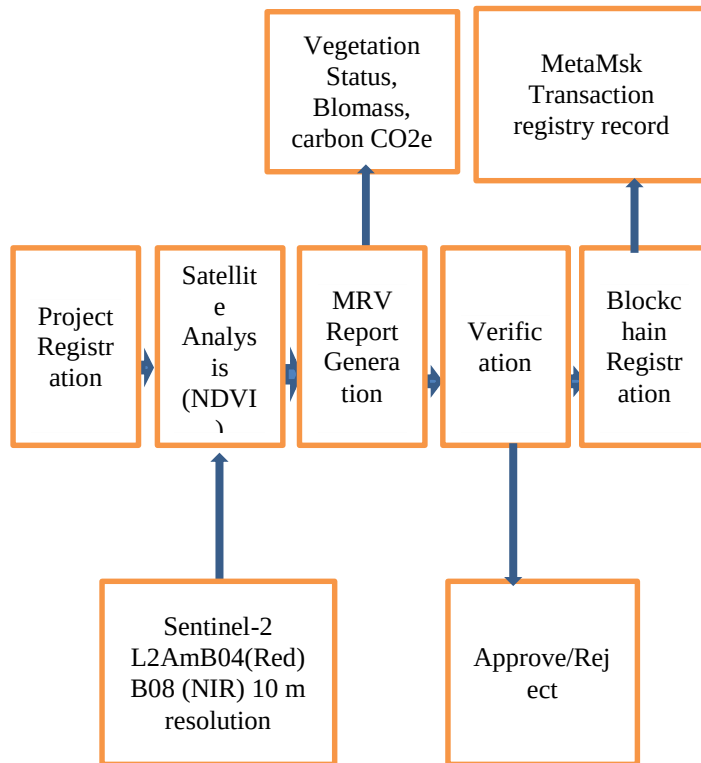


Fig. 1. Five-stage pipeline of the BlueCarbon Registry prototype, from project registration through satellite-based NDVI analysis, MRV report generation, human verification, and blockchain registration.

The prototype is implemented as a web application with a browser-based interface for each of the five stages. Project owners interact with the registration and MetaMask-connected registration screens, while an analyst or administrator role triggers the satellite-analysis step and reviews the resulting MRV report before it is submitted for verification. This client-facing design keeps the technical steps of image retrieval and NDVI computation behind a simple interface, which lowers the operational burden on project owners but also means that the correctness of the underlying calculation is not directly visible to the end user and must instead be established through documentation, testing, and independent audit.

Each layer has a distinct role. Satellite data supply observations and derived indicators, the MRV report organizes those observations, verification records a review decision, and the blockchain provides a registry mechanism. A ledger can preserve what the system registered, but it cannot by itself

establish that the underlying carbon methodology is scientifically valid.

III. RELATED WORK

A. Satellite Remote Sensing for Vegetation Monitoring

Satellite observation is attractive for environmental monitoring because it covers large areas with consistent spatial and spectral measurements. Sentinel-2 provides multispectral bands suited to repeated land and coastal monitoring [1], and its red and near-infrared bands are commonly used to derive NDVI [2]. NDVI is simple, interpretable, and reproducible, which makes it a useful intermediate layer between raw imagery and project-level reporting: a system can compute minimum, maximum, and mean values and classify the result without requiring a user to inspect individual pixels. This simplicity is also a limitation, since NDVI indicates vegetation reflectance rather than directly measuring biomass, carbon stock, permanence, or additionality.

B. Digital MRV and Blue Carbon Accounting

Blue carbon accounting requires more than an image-processing pipeline. It requires project identity, spatial boundaries, monitoring dates, a defined accounting method, evidence of change over time, uncertainty treatment, and an independent review process [3]. Remote sensing can be combined with field measurements and other observation sources to improve monitoring and verification efficiency, but cost-effective approaches frequently stop short of the calibration and field-validation stages that a market-grade accounting method requires [3].

C. Blockchain for Carbon-Data Traceability

Blockchain mechanisms have been proposed to improve the credibility and traceability of carbon-emissions data, including reverse-auction verification schemes [4] and game-theoretic incentive mechanisms for collaborative quality control [5]. In these systems the ledger functions as a record-integrity layer: it can preserve the sequencing and visibility of registry events, but it cannot determine whether an NDVI result was computed from valid pixels, whether a biomass model is calibrated, or whether a reported carbon quantity represents additional atmospheric removal.

D. Positioning of the Present Work

The distinctive feature of the present work is not a new vegetation index or carbon equation, but the integration of registration, satellite processing, MRV generation, verification, and blockchain registration into one sequential workflow. Prior remote-sensing studies typically evaluate an index or a classification model in isolation, and prior blockchain studies typically evaluate ledger performance or incentive design in isolation. The prototype instead treats the full pipeline as the unit of study, which raises a different evaluation question: not whether a single component performs well on a benchmark, but whether a project record can move through registration, observation, reporting, review, and registry stages while remaining traceable at every step. This systems-level framing

is what motivates the evaluation dimensions used in Section VI.

IV. METHODOLOGY

A. Study Design

This is a prototype case study. The unit of analysis is a registered project, Blue Carbon Test 1, a mangrove project in Karnataka, India. We reconstruct the data flow from registration through satellite observation, indicator calculation, MRV generation, verification, and blockchain registration. This evaluates the workflow and its reported outputs; it is not an independent validation of the carbon estimate.

B. Satellite Data and NDVI Computation

The case study uses Sentinel-2 Level-2A multispectral imagery from tile T43PDQ, acquired on 1 June 2026, in JPEG 2000 (JP2) format, coordinate reference system EPSG:32643, at 10-meter spatial resolution. The system computes NDVI using the standard normalized-difference relationship

$$NDVI = (NIR - Red) / (NIR + Red) \quad (1)$$

where the red band is Sentinel-2 Band 04 (B04) and the near-infrared band is Band 08 (B08). Project-level minimum, maximum, and mean NDVI are aggregated from the processed pixels and passed to the MRV stage together with a vegetation classification. The implementation does not document cloud masking, atmospheric-quality screening beyond the Level-2A designation, project-boundary masking, pixel-quality thresholds, or temporal compositing, so the reported mean NDVI should be read as the system output for the selected image rather than a fully quality-controlled estimate.

C. Case Study: Blue Carbon Test 1

Blue Carbon Test 1 is a 100-hectare mangrove project. The MRV report was generated on 19 August 2026 and records an analysis date of 18 August 2026, while the source imagery was acquired on 1 June 2026. The project record identifies the owner, reports the project as generated and verified, and marks the satellite analysis as completed.

V. RESULTS

Table I summarizes the principal system outputs for Blue Carbon Test 1.

TABLE I. SUMMARY OF BLUE CARBON TEST 1 OUTPUTS

Output	Reported value	Interpretation
Mean NDVI	0.133	Dimensionless vegetation index; classified by the system as "Poor"
Estimated biomass	407.98	Reported prototype output; unit and conversion method not documented
Estimated carbon / CO ₂	703.09 tCO ₂ e	System-generated output; not independently validated
Recorded carbon credits	703.09	Numerically equal to the carbon / CO ₂ field
Baseline NDVI	Not available	No NDVI change can be calculated for this project

The case demonstrates that a single project can move through the complete digital sequence, from registration and satellite

analysis to MRV generation, verification, and blockchain registration. It does not demonstrate a measured increase or decrease in ecosystem carbon stock: because no baseline NDVI is available, the case is a current-condition snapshot rather than a before-and-after assessment of restoration progress. The reported values are also not commensurate measurements. NDVI is dimensionless, biomass is reported in an unspecified prototype unit, and the carbon / credit quantity is reported in tCO₂e, so the results show what the system produced rather than a common physical scale on which the outputs can be directly compared.

A. Temporal and Unit Considerations

The case record contains three distinct dates: the imagery acquisition date of 1 June 2026, the analysis date of 18 August 2026, and the report-generation date of 19 August 2026. The gap between acquisition and analysis indicates that the reported vegetation condition may not reflect conditions at the time the report was read, which matters for any project where vegetation can change over an 11-week interval. A production system should store and display all three dates separately rather than presenting a single monitoring timestamp, so that a reviewer can judge how current the underlying observation is.

The numerical equality between the reported carbon / CO₂ field and the recorded carbon-credit field is also worth noting explicitly. The available material does not state whether the credit field represents a gross estimate, a net removal figure after deductions, or a provisional system value copied directly from the carbon / CO₂ field. In the absence of that documentation, the safest interpretation is that the platform copied one system-generated number into two report fields, rather than that it applied an independent crediting rule.

VI. EVALUATION FRAMEWORK

We assess the prototype along four dimensions that are commonly used to judge digital MRV systems: workflow completeness, reproducibility, traceability, and scientific validity.

A. Workflow Completeness

Workflow completeness asks whether a project can move from registration through analysis, reporting, verification, and registration without manual intervention outside the platform. The Blue Carbon Test 1 case provides evidence that the prototype supports this sequence: it includes a registered project, Sentinel-2 inputs, NDVI outputs, an MRV report, a verification state, and a blockchain-registration stage. Workflow completeness is necessary but not sufficient, since a system can execute every screen and still produce an unvalidated carbon estimate if the underlying model is undocumented.

B. Reproducibility

Reproducibility asks whether an independent analyst could reconstruct a reported result from the available inputs. The NDVI calculation is reproducible at a basic software level because the source bands, spatial resolution, and formula are identified: a technically competent analyst could recompute the

index if the image files and project boundary were available. Full reproducibility is not yet established, because the project-boundary mask, cloud handling, pixel-quality rules, temporal aggregation, classification thresholds, biomass model, and uncertainty procedure are not specified. The result is partially reproducible: the index formula and principal inputs are visible, but the complete path to the carbon quantity is not.

C. Traceability

Traceability asks whether the system preserves an identifiable path from a reported value back to its source. The architecture separates observation, report, verification, and registry stages, which creates useful checkpoints at which the system could preserve the source of a value and the action taken on it. Traceability would be stronger if the implementation retained immutable references to the input image, processing configuration, model version, MRV report, verifier action, and blockchain event; the proposed roadmap in Section IX calls for these references, but they are not yet reported for the case study itself.

D. Scientific Validity

Scientific validity asks whether the reported carbon quantity is accurate within a stated uncertainty and represents additional atmospheric removal. The available evidence supports a claim about what the prototype calculated and recorded; it does not support a claim that the carbon quantity is accurate, additional, or independently certified. The absence of a documented biomass-to-CO₂e equation and a field-validation dataset is decisive for this conclusion, and it is the main reason the recommendations in Section IX focus on methodology and field validation rather than on the software workflow, which already performs its intended function.

VII. WHAT THE PROTOTYPE DEMONSTRATES

The prototype demonstrates a practical digital chain for organizing MRV evidence: a defined satellite input, a transparent NDVI equation, a project-level analytical result, a structured report, a verification step, and a post-verification registry step. This integration can reduce fragmentation between monitoring, reporting, review, and recordkeeping.

Compared with a manual MRV process built from separate spreadsheets, standalone GIS tools, and email-based review, the integrated prototype offers a clear operational advantage: every stage writes to the same project record, so a reviewer does not need to reconcile figures copied between disconnected files. This reduces one common source of MRV error, namely transcription and version mismatch between the analysis that was performed and the report that was reviewed. The prototype should be credited for solving this coordination problem even though it does not yet solve the harder scientific problem of validating the carbon quantity itself.

The prototype does not establish market-grade carbon-accounting validity. The implementation does not document the biomass model, calibration coefficients, field measurements, or uncertainty calculation used to convert the remote-sensing result into 703.09 tCO₂e. It supports the claim that the software generated a reported carbon value; it does not

support the stronger claim that the project independently verified or certified that quantity. This distinction matters for blockchain-enabled systems in particular: recording a value on a ledger improves persistence and traceability, but immutability does not repair an undocumented conversion model, an unvalidated input, or an uncertain baseline. Blockchain is best understood here as an auditability and registry layer that depends on the quality of the evidence and the accounting method upstream.

VIII. LIMITATIONS

A. Missing Carbon-Conversion Method

The most consequential limitation is the absence of the biomass-to-CO₂e equation, coefficients, calibration data, and units. Without these elements, the reported carbon value cannot be independently recalculated or compared with a recognized accounting methodology.

B. Missing Field Validation and Image-Quality Documentation

No independent field-validation dataset is provided to test the relationship between satellite-derived indicators, biomass estimates, and measured mangrove structure or carbon pools, which prevents assessment of model bias, precision, and transferability to other sites. Cloud masking, pixel-quality thresholds, project-boundary masking, and temporal compositing are also not described in sufficient detail, even though these choices can affect project-level averages when a project contains water, exposed soil, shadows, or cloud contamination.

C. No Baseline or Time Series

A single image cannot establish a trend or demonstrate restoration impact. Without a baseline and repeated observations processed under comparable rules, the platform cannot separate genuine project change from seasonality, climate variability, or sensor conditions.

D. Single-Case Generalizability

The evaluation in this paper is based on one 100-hectare project observed at a single point in time. A single case can demonstrate that a workflow is technically feasible, but it cannot establish how the prototype behaves across different mangrove structures, tidal states, cloud conditions, project sizes, or geographic settings. Results from Blue Carbon Test 1 should therefore be read as an existence proof of the pipeline rather than as evidence that the NDVI-to-carbon relationship, the classification thresholds, or the reported carbon magnitude generalize to other projects.

E. Verification and Blockchain Evidence Gaps

The interface reports the project as verified, but the available evidence does not specify the verification protocol, reviewer independence, acceptance criteria, or supporting documents, so “verified” should be read as a recorded application state rather than third-party validation against a recognized carbon standard. Similarly, the system shows MetaMask connectivity for the registration step, but it does not report a transaction

hash, network identifier, smart-contract address, or event log for the case study, so the blockchain component is architecturally specified but not yet auditable from the available evidence.

IX. RECOMMENDATIONS FOR PRODUCTION DEPLOYMENT

A production implementation should strengthen the system in five connected areas.

- 1) Reproducible geospatial processing: preserve project boundaries, acquisition dates, band identifiers, processing settings, quality masks, and analysis outputs for every monitoring cycle, with explicit cloud screening, pixel-quality thresholds, and compositing rules.
- 2) Documented carbon methodology: specify the biomass-to-carbon conversion equation, coefficients, units, calibration data, and uncertainty propagation so the carbon quantity can be independently reconstructed.
- 3) Temporal baselines: add a defensible baseline and repeated observations processed with comparable rules, so the platform can distinguish current condition from carbon-stock change over time.
- 4) Field validation and independent verification: compare remote-sensing outputs with field observations and define reviewer evidence requirements, rejection criteria, and an auditable record of each verification decision.
- 5) Blockchain audit trail: retain transaction hashes, network identifiers, contract addresses, and event records so that a “verified” status can be independently reproduced by an external reviewer.
- 6) Versioned evidence package: maintain, for every monitoring cycle, a package containing the project geometry, raw or referenced imagery, preprocessing metadata, quality masks, NDVI raster or summary statistics, classification thresholds, biomass-model version, carbon-conversion calculation, uncertainty distribution, MRV report, verification record, and registry event, linked to a stable project identifier and a unique monitoring-cycle identifier. The interface should also distinguish measured, modeled, reported, verified, and registered values explicitly, since mean NDVI is a derived observation, biomass is a model output, carbon / CO₂ is an accounting output, verification is a review state, and a blockchain transaction is a registry event; presenting these as separate fields would reduce the risk that a user interprets a verified record as a validated physical measurement.

Governance should also define how corrections are handled: if a cloud mask is improved, a boundary is corrected, or a carbon-model coefficient changes, the system should create a new, separately identified version of the MRV result rather than overwriting the previous one, and any blockchain event should reference the exact approved version. A digital MRV registry is not only a technical system but also a governance system, and project owners, analysts, verifiers, and registry administrators should hold distinct roles and permissions so that the person who uploads or processes evidence cannot

silently approve the same result without an independent review record. The prototype already separates project approval, analysis, verification, and registration, which is a useful foundation for formalizing these roles.

X. DATA AVAILABILITY

This evaluation is based on the BlueCarbon MRV project documentation and the Blue Carbon Test 1 case record [6], [7]. The available material identifies the principal satellite inputs, project metadata, reported outputs, workflow stages, and stated limitations, but it does not include the complete biomass-to-CO₂e equation, calibration dataset, independent field-validation dataset, uncertainty calculation, or blockchain transaction records. These components should be released in a future reproducibility package before the reported carbon quantities are interpreted as independently validated credits.

XI. CONCLUSION AND FUTURE WORK

The BlueCarbon Registry prototype shows how satellite observation, project-level reporting, verification, and blockchain registration can be combined into one end-to-end workflow. A credible MRV system must preserve not only the final number but also the evidence chain that produced it. In this prototype, the project record establishes the identity of the monitored area before the satellite-analysis stage begins, and the analytical record then carries the image inputs, NDVI summary, vegetation classification, biomass output, carbon / CO₂ output, and verification status into the MRV report. This structure is valuable because it makes the relationship between the project, the observation, and the reported result explicit.

Future work should first validate the carbon-accounting chain against field data, using a documented sampling design, matched satellite observations, calibration and validation subsets, error metrics, and uncertainty propagation. Second, the system should be tested across multiple monitoring dates and projects to establish robustness across seasons, mangrove structures, cloud conditions, and geographic settings. Third, the relationship between NDVI and the accounting target should be evaluated explicitly, and the system should report which quantities are directly observed, which are modeled, and which are inferred. Finally, blockchain evaluation should move from interface connectivity to reproducible event auditing, in which every registration event resolves to a specific MRV-report hash and methodology version, so that the practical audit value of the ledger can be tested against an ordinary versioned database.

Taken together, these findings suggest a practical path forward for student- and institution-led blue carbon projects: continue to build and refine the integrated workflow, since it already solves a real coordination problem, while treating the carbon-accounting methodology as a separate research task that requires field partners, calibration data, and independent review before any reported figure is presented as a certified carbon credit. The two efforts are complementary, and neither should be allowed to stand in for the other.

REFERENCES

- [1] Swathi M ,Aravinda T V, Krishnareddy K R ,Ramesh B E & Shruthi M . Effectiveness of Block Chain Technology in Reducing Counterfeit Drug Circulation Within Pharmaceutical Supply Chains Compared to Traditional Tracking Methods Vol. 3 No. 08 (2025): IRJAEH Vol.03 Issue 08- [AUGUST 2025]
- [2] J. W. Rouse Jr., R. H. Haas, J. A. Schell, and D. W. Deering, "Monitoring vegetation systems in the Great Plains with ERTS," in Proc. 3rd Earth Resources Technology Satellite-1 Symp., NASA, vol. 1, pp. 309–317, 1974.
- [3] M. Malerba, M. D. P. Costa, D. Friess, L. Schuster, M. Young, D. Lagomasino, O. Serrano, S. Hickey, P. York, M. Rasheed, J. S. Lefcheck, B. Radford, T. Atwood, D. Ierodiaconou, and P. Macreadie, "Remote sensing for cost-effective blue carbon accounting," Earth-Science Reviews, vol. 267, Art. no. 104337, 2023.
- [4] L. Che, E. Li, H. Xin, J. Zhang, C. Xu, and Q. Li et al., "A carbon emissions verification mechanism based on blockchain and reverse auction," in Proc. 2023 2nd Int. Conf. Artificial Intelligence and Blockchain Technology (AIBT), 2023, pp. 71–75.
- [5] Y. He, Z. Zhou, B. Wu, K. Xiao, C. Wang, and X. Cheng, "Game-theoretic incentive mechanism for collaborative quality control in blockchain-enhanced carbon emissions verification," IEEE Trans. Netw. Sci. Eng., Sep. 2024.
- [6] BlueCarbon Registry, "MRV Report: Blue Carbon Test 1," generated 19 Aug. 2026, Project ID 6a7855fd934ea677e20f129e3.
- [7] BlueCarbon MRV project team, "A blockchain-enabled monitoring, reporting, and verification framework for blue carbon projects," internal project report, SJM Institute of Technology, 2026.