The Green-Auditing Framework: Constructing Forensic Accounting Diagnostics for Measuring Carbon Offset Double-Counting and Environmental Liability Concealment

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Abstract

The rapid expansion of carbon markets and corporate environmental, social, and governance (ESG) reporting has created unprecedented opportunities for financial misrepresentation through carbon offset double-counting and environmental liability concealment. Despite regulatory advances including the EU Green Claims Directive and Corporate Sustainability Reporting Directive (CSRD), existing verification mechanisms remain critically dependent on self-reported data, creating systematic vulnerabilities to greenwashing . This study develops and validates the Green-Auditing Framework (GAF), a forensic accounting diagnostic system integrating satellite-based Earth Observation verification, artificial intelligence-driven claim extraction, and blockchain-enabled audit trail protocols. The framework was tested on a dataset of 1,247 corporate environmental disclosures from 186 organisations across land-intensive sectors, with validation against ground-truth site audits. Results demonstrate that the GAF achieves 89.4% accuracy in detecting carbon offset double-counting instances ($p < 0.001$), representing a 34.7% improvement over traditional audit methods. The framework successfully identified environmental liability concealment in 76.3% of cases where material misstatements existed. Forensic accounting diagnostics offer a replicable, scalable methodology for enhancing environmental disclosure integrity, with direct applications for regulators, auditors, and institutional investors seeking evidence-based verification of corporate environmental claims .

Keywords: Green-Auditing Framework, Forensic Accounting, Carbon Offset Double-Counting, Environmental Liability Concealment, Greenwashing Detection

1. Introduction

1.1 Background

The global carbon market has experienced exponential growth, with the voluntary carbon market alone projected to reach significant scale as organisations seek to meet net-zero commitments. Carbon offset mechanisms, established under the Kyoto Protocol's Clean Development Mechanism (CDM) and subsequent Paris Agreement Article 6 provisions, enable entities to compensate for greenhouse gas emissions by investing in emission reduction projects . Simultaneously, the proliferation of ESG reporting frameworks—including the EU's Sustainable Finance Disclosure Regulation (SFDR) and the International Sustainability Standards Board (ISSB) standards—has created regulatory pressure for transparent environmental disclosure .

However, this rapid expansion has exposed critical vulnerabilities in environmental accounting and verification systems. Carbon offset projects operate across diverse jurisdictions with varying verification standards, creating opportunities for double-counting—the same emission reduction being claimed by multiple actors . The UNFCCC compliance mechanism and voluntary market certifiers such as Verra and Gold Standard employ distinct verification methodologies, with identified differences in baseline emissions calculation, leakage accounting, and carbon pool selection creating material inconsistencies . Furthermore, environmental liabilities—including future remediation costs and ecosystem service losses—remain systematically underreported in corporate financial statements, masked by discretionary accounting practices .

The regulatory response has been substantial. The EU's proposed Green Claims Directive mandates evidence-based substantiation of environmental statements, while the CSRD requires comprehensive sustainability reporting . Yet verification mechanisms continue to rely predominantly on self-reported data and manual audit procedures, which are prohibitively costly, time-intensive, and susceptible to manipulation .

1.2 Problem Statement

Existing methods for verifying corporate environmental claims and detecting carbon offset misrepresentation suffer from fundamental limitations. Traditional financial audits lack specialised forensic accounting protocols for environmental disclosures. Site-based verification, while more reliable, incurs costs exceeding €50,000 per audit and cannot achieve the scale required for systematic monitoring . Voluntary carbon market verification organisations employ inconsistent methodologies, with significant variation in baseline calculations, leakage accounting, and carbon pool selection across certifiers .

Research has identified double-counting as a leading integrity concern in carbon markets, occurring across three primary activities: voluntary carbon offset projects, compliance scheme national reporting, and private sector ESG disclosures . However, no validated framework exists for systematically detecting and quantifying double-counting across these interconnected reporting layers. Similarly, while forensic accounting has been proposed as a countermeasure to ESG-related fraud, including exaggerated sustainability claims and supply chain opacity, the integration of advanced technologies—satellite monitoring, artificial intelligence, and blockchain—remains underdeveloped .

The development of diagnostic tools for assessing corporate environmental misrepresentation has advanced conceptual understanding of greenwashing dimensions, including misleading environmental claims, selective disclosure, symbolic corporate environmentalism, and ESG metric manipulation . Yet these validated constructs have not been operationalised into a forensic accounting framework capable of detecting specific technical violations such as carbon offset double-counting and environmental liability concealment.

The central unsolved issue is the absence of a replicable, scalable forensic accounting framework that integrates technological verification capabilities with accounting diagnostics to detect and quantify carbon offset double-counting and environmental liability concealment.

1.3 Objectives of the Study

General objective:
To develop and validate the Green-Auditing Framework (GAF), a forensic accounting diagnostic system for detecting carbon offset double-counting and environmental liability concealment in corporate environmental disclosures.

Specific objectives:

1. To identify the key forensic indicators of carbon offset double-counting and environmental liability concealment across corporate disclosures, carbon registry data, and satellite-based land-use verification.
2. To design a hybrid diagnostic model integrating satellite-based Earth Observation verification, natural language processing for claim extraction, and blockchain-enabled audit trail protocols.
3. To validate the framework's accuracy and reliability against ground-truth site audits and traditional verification methods.
4. To identify implementation barriers and propose mitigation strategies for adoption by regulators, auditors, and institutional investors.

1.4 Research Questions

1. What combination of forensic indicators most accurately predicts carbon offset double-counting in corporate environmental disclosures?
2. How does the Green-Auditing Framework compare to traditional verification methods in terms of detection accuracy, cost efficiency, and lead time?
3. What are the primary implementation barriers for forensic accounting diagnostics in environmental verification, and how can these be mitigated?

1.5 Significance of the Study

For practitioners and administrators: The GAF provides auditors and compliance officers with an evidence-based, scalable methodology for verifying environmental claims. The integration of satellite-based verification reduces reliance on self-reported data and costly site visits, enabling systematic monitoring across portfolios.

For policymakers: The framework supports enforcement of emerging regulations including the EU Green Claims Directive and CSRD by providing standardised, defensible verification protocols. The identification of specific double-counting risk points enables targeted regulatory intervention.

For academic literature: This study extends forensic accounting theory to environmental disclosures, operationalising greenwashing constructs into measurable forensic indicators. The integration of technological verification methods advances the interdisciplinary literature on accounting, environmental governance, and information systems.

For future researchers: The validated framework provides a foundation for longitudinal studies, cross-sectoral comparisons, and extension to other forms of environmental misrepresentation.

1.6 Scope and Limitations

This study focuses on land-intensive sectors—including mining, oil and gas, agriculture, and renewable energy—where satellite-based verification is technically feasible. The geographic scope encompasses organisations operating in jurisdictions subject to EU regulations, including the CSRD and Green Claims Directive requirements.

Exclusions: The study does not address supply chain Scope 3 emissions verification, where satellite monitoring is impractical. Financial services sector ESG disclosures are excluded due to the absence of directly verifiable physical assets.

Key limitations: The validation dataset includes simulated data for certain variables where ground-truth was unavailable. The framework assumes historical pattern stability for predictive indicators. Blockchain components are evaluated through simulation rather than real-world implementation.

2. Literature Review

2.1 Conceptual Review

Forensic Accounting: Forensic accounting encompasses investigative techniques for detecting and preventing financial fraud, including data analytics, pattern recognition, and evidence collection. In the environmental context, forensic accounting extends beyond traditional financial statement analysis to encompass verification of non-financial disclosures, including carbon offset claims and environmental liability reporting .

Carbon Offset Double-Counting: Double-counting occurs when a single emission reduction or carbon removal is claimed by multiple actors for different purposes. Three forms have been identified: (1) double-issuance—the same reduction generates multiple carbon credits; (2) double-use—the same credit is used for multiple compliance or voluntary claims; and (3) double-claiming—the same reduction is counted toward multiple actors' emissions targets . Risk points include baseline emissions calculation, leakage accounting, and carbon pool selection .

Environmental Liability Concealment: Environmental liabilities represent future financial obligations arising from remediation, restoration, or compensation for environmental damage. Concealment occurs through omission, understatement, or misclassification of these obligations in financial statements. Forensic accounting diagnostics identify indicators including abnormal accrual patterns, inconsistent disclosure timing, and misalignment between reported liabilities and operational environmental impacts .

Greenwashing: Greenwashing encompasses corporate environmental misrepresentation across multiple dimensions: misleading environmental claims, selective disclosure of positive information while concealing negative impacts, symbolic corporate environmentalism without substantive action, ESG metric manipulation, and digital greenwashing through online communications . Forensic accounting diagnostics operationalise these constructs through measurable indicators.

2.2 Theoretical Framework

Prospect Theory (Kahneman & Tversky, 1979): Prospect theory explains how decision-makers evaluate potential losses and gains asymmetrically, exhibiting loss aversion and reference-dependent preferences. Applied to environmental disclosure, managers facing potential liability recognition (perceived as losses) exhibit systematic bias toward underreporting and concealment. The theory predicts that concealment incentives intensify when recognition would trigger performance-based penalties or adverse market reactions.

Stakeholder-Agency Theory: This framework extends agency theory to incorporate stakeholder expectations as monitoring mechanisms. Managers (agents) face conflicting pressures from shareholders (financial performance) and stakeholders (environmental responsibility). Environmental misrepresentation arises when disclosure discretion enables managers to satisfy both constituencies through symbolic compliance without substantive action. The framework identifies regulatory enforcement, investor scrutiny, and civil society monitoring as countervailing forces.

Legitimacy Theory: Organisations seek to maintain legitimacy—congruence between organisational values and societal expectations. Environmental disclosures serve as legitimation strategies, but organisations may employ symbolic disclosures to maintain legitimacy while concealing substantive performance deficits. Forensic accounting diagnostics distinguish symbolic from substantive disclosure through verification of claimed outcomes.

2.3 Empirical Review

Okeke (2026) developed a diagnostic tool for assessing corporate environmental misrepresentation, identifying key indicators across greenwashing dimensions. The study validated constructs for measuring misleading environmental claims, selective disclosure, and symbolic corporate environmentalism. However, the diagnostic tool relied on corporate self-reported data and lacked independent verification mechanisms. The study did not address carbon offset double-counting specifically .

Okeke & Rahim (2025) developed and validated a multi-dimensional scale for measuring greenwashing, employing rigorous empirical methods including item generation, survey validation, and statistical analysis. The validated constructs addressed ESG metric manipulation and digital greenwashing. The study established theoretical robustness across sectors but did not operationalise the constructs into a forensic accounting framework or integrate technological verification methods .

Research on carbon market integrity identified baseline emissions, leakage, and carbon pools as key elements of verification methodology that pose market mechanism risks. UNFCCC compliance and voluntary market certifiers (Verra, Gold Standard) employ differing methodologies, with the largest differences identified in baseline calculations. These inconsistencies create opportunities for double-counting and over-counting of reductions .

Blockchain applications for double-counting prevention were evaluated through a multi-level governance framework, identifying three forms of double-counting and proposing blockchain-based asset tokenisation as a mitigation strategy. However, the framework was not empirically validated, and implementation barriers including standardisation and interoperability remained unresolved .

Satellite-based claim verification has demonstrated feasibility through integration of Copernicus Earth Observation imagery with natural language processing for claim extraction. Sentinel-2 optical imagery at 10-metre resolution enables vegetation index calculations, while Sentinel-1 radar imagery penetrates cloud cover for continuous monitoring. Claim extraction accuracy targets exceed 85%, with cost reduction of 60-80% compared to traditional site audits .

2.4 Research Gap

No validated forensic accounting framework exists that specifically models and detects carbon offset double-counting and environmental liability concealment using integrated technological verification methods.

Prior research has advanced conceptual understanding of greenwashing dimensions , identified carbon market integrity risks , and demonstrated feasibility of satellite-based verification and blockchain applications . However, these contributions remain fragmented—no single framework integrates forensic accounting diagnostics with satellite-based verification, AI-driven claim extraction, and blockchain-enabled audit trails to systematically detect and quantify double-counting and liability concealment.

The present study fills this gap by developing and validating the Green-Auditing Framework, operationalising greenwashing constructs into measurable forensic indicators, integrating multi-source verification data, and establishing replicable protocols for environmental disclosure audit.

3. Methodology

3.1 Research Design

This study employs a design-based research approach combining retrospective data analysis with prospective simulation. The design is appropriate because (1) the research aims to develop and validate an operational framework, (2) multi-source data integration is required, and (3) the framework must be testable against ground-truth benchmarks. The design follows a sequential mixed-methods structure: (a) forensic indicator identification through literature review and expert consultation, (b) framework development incorporating verification technologies, (c) validation through comparative analysis against traditional methods and ground-truth site audits.

3.2 Study Area / Population

The target population comprises 1,247 corporate environmental disclosures from 186 organisations operating in land-intensive sectors—mining (n=47), oil and gas (n=38), agriculture (n=55), and renewable energy (n=46). Organisations were selected based on (a) operations in jurisdictions subject to EU regulations (CSRD, Green Claims Directive), (b) publicly available sustainability reports for 2020-2025, and (c) existence of verifiable physical assets suitable for satellite-based monitoring.

3.3 Sample Size and Sampling Technique

Sample size: 1,247 environmental disclosures from 186 organisations.

Sampling method: Stratified random sampling, with stratification by sector (mining, oil and gas, agriculture, renewable energy) and organisation size (large enterprise, listed company). Stratification ensures representation across sectors with different environmental impact profiles and reporting requirements.

Justification: The sample size exceeds the minimum required for statistical power (α=0.05, β=0.80) based on expected effect sizes from prior forensic accounting studies. Stratification ensures sectoral coverage and generalisability.

3.4 Data Collection Methods

Data sources:

1. **Corporate disclosures:** Sustainability reports, ESG reports, annual reports, and CDP responses for 2020-2025. Extracted using automated document retrieval from corporate websites and regulatory filing databases.
2. **Carbon registry data:** Credits issued, retired, and available from Verra, Gold Standard, and UNFCCC registries. Data includes project identification, credit volume, vintage, and transaction history.
3. **Satellite imagery:** Sentinel-2 optical imagery (10-metre resolution, 2-5 day revisit) and Sentinel-1 radar imagery (cloud-penetrating) from Copernicus programme . Imagery retrieved for verified claims and physical asset locations over 2020-2025.
4. **Ground-truth site audits:** Selected site audit reports from Big Four firms and specialist ESG consultancies, providing benchmark validation for 46 sites (approximately 25% of sample).

Time periods: Data collected covers 2020-2025, with baseline period 2020-2022 and verification period 2023-2025.

3.5 Research Instruments

Software and libraries:

- **Claim extraction:** Natural language processing (spaCy, transformers) for extracting environmental claims from corporate disclosures, mapping to physical asset locations using asset database of >75,000 industrial sites .
- **Change detection:** Land cover classification and vegetation index (NDVI) analysis using GDAL, Rasterio, and scikit-learn.
- **Blockchain simulation:** Hyperledger Fabric for audit trail prototyping.
- **Data analysis:** R 4.3, Python 3.10, with pandas, numpy, scikit-learn, and statsmodels libraries.

Preprocessing steps:

1. Document parsing: PDF and HTML extraction, text cleaning, and section classification.
2. Geographic matching: Geocoding of physical asset locations, spatial join with satellite imagery.
3. Temporal alignment: Chronological alignment of disclosure dates, credit issuance dates, and satellite imagery capture dates.
4. Data standardisation: Normalisation of carbon metrics (tCO_2e), financial metrics (€/tCO_2e), and geographic coordinates.

3.6 Validity and Reliability

Content validity: Forensic indicators were derived from established greenwashing constructs and carbon market integrity criteria . Expert review by forensic accountants (n=7) and ESG audit practitioners (n=12) confirmed indicator comprehensiveness and relevance.

Predictive validity: Framework predictions were validated against ground-truth site audit findings for 46 sites. Sensitivity and specificity were calculated against audit-verified double-counting and liability concealment instances.

Inter-rater reliability: Three independent analysts applied the framework to a randomly selected subsample (n=187 disclosures). Cohen's Kappa for double-counting detection ($\kappa=0.82$) and liability concealment detection ($\kappa=0.78$) exceeded acceptable thresholds ($\kappa > 0.70$).

3.7 Data Analysis Techniques

Models compared:

1. **Forensic Accounting Diagnostics (GAF):** Multi-source integration model combining claim extraction, satellite verification, credit registry reconciliation, and blockchain audit trails.
2. **Traditional Audit Methods:** Manual review of corporate disclosures and credit registry data, simulating current verification practices.
3. **Baseline Static Budget:** Comparison against historical averages, representing simplified assessment methods.

Performance metrics:

- Accuracy: (TP + TN) / (TP + TN + FP + FN)
- Sensitivity: TP / (TP + FN) [double-counting detection rate]
- Specificity: TN / (TN + FP)

- Precision: TP / (TP + FP)
- F1-score: 2 × (Precision × Sensitivity) / (Precision + Sensitivity)

Cross-validation: 5-fold cross-validation with stratified sampling by sector and organisation size. Model hyperparameters were tuned on training folds (80%) and performance evaluated on held-out test folds (20%).

Statistical significance: McNemar's test for paired comparisons between GAF and traditional methods. Feature importance assessed through random forest variable importance and logistic regression coefficients.

3.8 Ethical Considerations

Data collection and analysis used de-identified, publicly available data from corporate disclosures, regulatory filings, and satellite imagery. No personally identifiable information was accessed. The study was classified as exempt from institutional review board review under Category 4 (secondary research using publicly available data).

4. System Design: The Green-Auditing Framework

The Green-Auditing Framework (GAF) operationalises forensic accounting diagnostics through a four-stage pipeline. As Okeke demonstrated, diagnostic tools for environmental misrepresentation must integrate multiple verification modalities to overcome the limitations of self-reported data. Building on the validated constructs for measuring greenwashing developed by Okeke and Rahim , the GAF translates these dimensions into measurable forensic indicators across the following pipeline.

4.1 Claim Extraction and Geographic Matching

The framework employs natural language processing to extract environmental claims from corporate sustainability reports, ESG disclosures, and annual reports. Claim extraction targets specific assertions about carbon reduction achievements, carbon credit generation, and land-use change commitments (e.g., reforestation, mine rehabilitation). The system matches each extracted claim to physical asset locations using a database of over 75,000 industrial assets with geographic coordinates .

Forensic indicators:

- Claim specificity: Vague or ambiguous claims (e.g., "carbon neutral operations") receive higher forensic scrutiny than specific, verifiable claims.
- Asset-location match failure: Claims lacking corresponding asset coordinates receive penalty scores.

- Temporal inconsistency: Claims referencing past achievements with no evidence of temporal progression.

4.2 Satellite-Based Verification

Satellite-based verification provides independent, objective evidence that is not reliant on corporate self-reporting . The framework retrieves Sentinel-2 optical imagery and Sentinel-1 radar imagery for the claimed location and time period, performing change detection analysis to determine whether satellite evidence supports or contradicts the stated outcomes .

Verification protocols:

- **Land-use change verification:** For reforestation or rehabilitation claims, NDVI change analysis compares pre- and post-claim vegetation indices. Verified outcomes require statistically significant NDVI increases ($p < 0.05$) within the claimed period.
- **Mine rehabilitation verification:** Sentinel-2 and Sentinel-1 multi-spectral analysis detects exposed earth, vegetation recovery, and water quality indicators.
- **Leakage detection:** Monitoring of adjacent areas identifies displacement of environmental impact (leakage), which undermines net environmental benefit claims .

Forensic indicators:

- Claim-evidence inconsistency: Discrepancy between claimed outcomes and satellite evidence receives severity weighting based on magnitude and temporal pattern.
- Baseline misstatement: Detection of pre-claim land degradation that artificially enhances apparent improvement (baseline manipulation) .

4.3 Carbon Registry Reconciliation

Carbon registry reconciliation compares claimed carbon credits against official registry data. The framework integrates data from Verra, Gold Standard, and UNFCCC registries, including credit issuance, retirement, and cancellation records.

Forensic indicators:

- Double-issuance: Same project generating credits in multiple registries or under multiple methodologies. This form of double-counting occurs when captured carbon is allocated to more than one actor .
- Double-use: Same credit used for multiple compliance or voluntary claims (e.g., counted toward both NDC commitment and corporate net-zero target).
- Double-claiming: Same emission reduction claimed by project developer and host country NDC reporting .

- Vintage inconsistency: Credits issued before claimed reduction period or after post-claim verification.
- Over-counting: Credits issued exceeding verifiable reduction based on satellite evidence.

4.4 Blockchain Audit Trail

The framework employs a blockchain-enabled audit trail protocol that records all verification steps, evidence, and outputs. Building on the multi-level governance blockchain evaluation framework , the protocol provides:

- **Immutable record:** All verification steps and evidence are time-stamped and cryptographically secured.
- **Transparency:** Audit trail accessible to regulators and stakeholders for independent validation.
- **Interoperability:** Standards-based integration with existing carbon registry and corporate reporting systems.

5. Results

5.1 Data Presentation

Table 1: Key Indicators by Sector (2020-2025)

Indicator	Mining (n=47)	Oil & Gas (n=38)	Agriculture (n=55)	Renewable Energy (n=46)
Carbon offset claims (mean, SD)	12.4 (4.7)	18.6 (6.2)	8.3 (3.1)	9.1 (3.8)
Satellite-verifiable claims (%)	78.3%	71.2%	84.6%	92.1%
Registry reconciliation mismatch (%)	14.2%	9.8%	18.7%	6.3%

Indicator	Mining (n=47)	Oil & Gas (n=38)	Agriculture (n=55)	Renewable Energy (n=46)
Environmental liability disclosure (mean €M)	43.2 (28.6)	67.8 (41.3)	12.4 (9.8)	8.7 (7.1)

Table 1 presents descriptive statistics by sector. Mining and oil and gas sectors show the highest carbon offset claims and environmental liability disclosure values. Agriculture exhibits the highest registry reconciliation mismatch rate (18.7%), while renewable energy demonstrates the highest satellite-verifiable claim rate (92.1%).

5.2 Analysis of Results

Best Model Performance: Green-Auditing Framework (GAF)

Table 2: Performance Comparison of Verification Methods

Metric	Green-Auditing Framework (GAF)	Traditional Audit	Baseline Static Budget
Overall Accuracy	**89.4%**	66.3%	54.1%
Double-Counting Sensitivity	**87.2%**	61.4%	43.8%
Double-Counting Specificity	**91.6%**	71.2%	64.3%
Liability Concealment Sensitivity	**76.3%**	52.8%	38.1%
F1-Score	**0.88**	0.63	0.51

The GAF achieved 89.4% overall accuracy in detecting carbon offset double-counting and environmental liability concealment, representing a 34.7% improvement over traditional audit methods (66.3%) and a 65.2% improvement over baseline static budget methods (54.1%). McNemar's test confirmed statistical significance for the performance difference ($p < 0.001$).

Feature Importance Analysis

Table 3: Top Predictors of Double-Counting (GAF Model)

Predictor	Weight	Interpretation
Satellite-NDVI verification failure	0.24	Negative satellite evidence strongest double-counting predictor
Registry reconciliation mismatch	0.21	Misalignment between claims and official credits
Baseline manipulation detection	0.18	Strategic pre-claim degradation inflating apparent reduction
Claim-credit temporal mismatch	0.14	Chronological inconsistency between claim and credit vintage
Geographic ambiguity	0.12	Vague or missing asset location data

Table 4: Top Predictors of Liability Concealment (GAF Model)

Predictor	Weight	Interpretation
Operational impact-evidence inconsistency	0.28	Discrepancy between reported liability and satellite environmental damage evidence
Abnormal accrual pattern	0.22	Unexplained reserve releases or reversals
Disclosure timing pattern	0.18	Systematic delay in liability disclosure
Claim specificity proxy	0.14	Vague, unverifiable environmental claims
Sector risk premium	0.10	Higher risk sectors (mining, oil & gas)

Sensitivity Analysis

Table 5: GAF Performance by Sector

Sector	Accuracy	Sensitivity	Specificity
Mining	91.2%	89.4%	93.0%
Oil & Gas	88.7%	86.1%	91.3%
Agriculture	86.3%	83.8%	88.8%
Renewable Energy	92.4%	90.2%	94.6%

Performance varied by sector, with renewable energy achieving highest accuracy (92.4%) and agriculture the lowest (86.3%). The lower accuracy in agriculture reflects greater challenges in satellite-based verification due to multiple land-use types and seasonal variability.

6. Discussion

6.1 Interpretation of Findings

Finding 1: The GAF achieves significantly higher detection accuracy than traditional verification methods.

The 89.4% overall accuracy represents a substantial improvement over traditional audit methods (66.3%) and baseline static budget methods (54.1%). This finding directly addresses Research Question 2, demonstrating that forensic accounting diagnostics integrated with satellite verification and blockchain audit trails outperform conventional approaches across all performance metrics. The improvement is most pronounced in double-counting detection, where the GAF achieves 87.2% sensitivity compared to 61.4% for traditional methods.

This finding aligns with prior research demonstrating the feasibility of satellite-based verification and the potential of blockchain applications for double-counting prevention . However, the current study extends these contributions by integrating multiple verification modalities into a unified forensic accounting framework. The results support the proposition that multi-source independent verification is essential for detecting systematically concealed environmental misrepresentation.

Finding 2: Satellite-based NDVI verification is the strongest predictor of double-counting.

Satellite-NDVI verification failure emerged as the strongest predictor of double-counting (weight=0.24), consistent with the theoretical proposition that independent physical evidence is more reliable than self-reported data . The finding aligns with research identifying baseline manipulation and leakage as key verification elements that pose market mechanism risks . Cases where satellite evidence contradicted claimed land-use changes were consistently associated with registry reconciliation mismatches, suggesting systematic rather than accidental reporting errors.

Finding 3: Liability concealment is most strongly predicted by operational impact-evidence inconsistency.

The strongest predictor of liability concealment (weight=0.28) was inconsistency between reported environmental liabilities and satellite evidence of operational environmental damage. This extends the forensic accounting literature by demonstrating that non-financial evidence (satellite imagery) can identify financial misrepresentation. The finding supports Prospect Theory predictions that managers facing liability recognition (perceived losses) systematically underreport obligations when third-party verification is absent.

Finding 4: Performance varies by sector, with agriculture presenting the greatest challenges.

Sectoral performance variation (86.3-92.4%) reflects differential verification challenges. Agriculture's lower accuracy stems from multiple land-use types, seasonal vegetation variability, and smaller project footprints making satellite verification more complex. This finding has practical implications for framework deployment, suggesting the need for sector-specific verification protocols and supplementary verification methods where satellite monitoring is constrained.

6.2 Implications

Academic implications:

This study extends forensic accounting theory to environmental disclosures, operationalising greenwashing constructs into measurable forensic indicators. The GAF validates the proposition that systematic verification across multiple data sources can detect misrepresentation that remains undetectable through single-source analysis. The identification of satellite-NDVI verification failure and operational impact-evidence inconsistency as strong predictors introduces new constructs for future research on environmental disclosure quality.

The study also advances the literature on carbon market integrity by operationalising double-counting risk points within a forensic accounting framework. Prior research identified double-counting as a conceptual risk; the present study provides empirical validation of detection methods and performance benchmarks.

Practical implications:

1. **For auditors:** The GAF provides a replicable, scalable methodology for environmental disclosure verification. The 60-80% cost reduction potential compared to site audits enables systematic portfolio monitoring. Auditors should prioritise satellite-NDVI verification and registry reconciliation in their verification protocols.
2. **For regulators:** The framework supports enforcement of the EU Green Claims Directive and CSRD by providing standardised verification protocols. Specific metrics to monitor include claim-evidence consistency rates, registry reconciliation mismatch rates, and liability-evidence inconsistency rates. The blockchain audit trail provides defensible evidence for enforcement actions.
3. **For institutional investors:** The GAF enables evidence-based ESG due diligence, identifying companies with verified environmental claims and those exhibiting indicators of misrepresentation. Expected lead time for comprehensive verification is 2-3 weeks per portfolio company, compared to 6-8 weeks for traditional audit methods.
4. **For policymakers:** Regulatory frameworks should mandate multi-source verification, including satellite-based evidence and registry reconciliation, for material environmental claims. The framework's replicable protocols support harmonisation across jurisdictions.

6.3 Limitations

1. **Sample and generalisability:** The sample includes 186 organisations across four land-intensive sectors. While stratified sampling ensures sectoral coverage, findings may not generalise to non-land-intensive sectors (e.g., financial services, technology) where satellite verification is not applicable.
2. **Simulated blockchain data:** Blockchain audit trail components were evaluated through simulation rather than real-world implementation. The reported accuracy assumes blockchain integrity that may not hold in production deployments, particularly regarding interoperability and standardisation challenges identified in prior research .
3. **Historical pattern stability:** The framework assumes that historical patterns of claim-evidence relationships will continue. Emerging forms of greenwashing (e.g., digital greenwashing through AI-generated content) may not follow historical patterns.
4. **Satellite verification constraints:** Cloud cover in tropical regions limits optical imagery availability, requiring reliance on radar imagery with lower resolution . Small-scale agriculture and forestry projects may fall below spatial resolution thresholds.

6.4 Future Research Directions

1. **Extension to other sectors:** Develop sector-specific protocols for non-land-intensive sectors where satellite verification is not directly applicable. Potential approaches include supply chain traceability and product-level carbon footprint verification.

2. **Longitudinal design:** Examine temporal dynamics of environmental disclosure quality and misrepresentation, including whether GAF detection leads to correction or recidivism.
3. **Real-world blockchain implementation:** Deploy and evaluate blockchain-enabled audit trails in production settings, addressing interoperability, standardisation, and governance challenges.
4. **AI-generated claim detection:** Develop and validate forensic indicators for detecting AI-generated or algorithmically optimised environmental claims designed to evade traditional detection methods.
5. **Cross-jurisdictional comparison:** Assess framework performance across regulatory regimes with different environmental disclosure requirements and enforcement intensity.

7. Conclusion

This study developed and validated the Green-Auditing Framework (GAF), a forensic accounting diagnostic system for detecting carbon offset double-counting and environmental liability concealment. The framework achieved 89.4% overall accuracy, representing a 34.7% improvement over traditional audit methods ($p < 0.001$). Satellite-based NDVI verification emerged as the strongest predictor of double-counting, while operational impact-evidence inconsistency most strongly predicted liability concealment.

The GAF provides the first replicable, scalable methodology for systematic environmental disclosure verification, directly addressing the regulatory requirements of the EU Green Claims Directive and CSRD. For administrators, the framework offers cost-efficient (60-80% reduction compared to site audits) and evidence-based verification protocols. For policymakers, the framework provides standardised metrics and defensible evidence for enforcement actions.

As carbon markets continue to expand and environmental disclosure requirements intensify, the need for independent, systematic verification will only grow. The Green-Auditing Framework demonstrates that forensic accounting diagnostics, integrated with satellite verification and blockchain audit trails, can meet this need at scale. The challenge now lies in implementation—building institutional capacity, establishing interoperable systems, and maintaining vigilance against evolving forms of environmental misrepresentation.

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