Standing Forests, Measurable Outcomes

The Climate Value of Forest Protection, Governance and Carbon Accountability

Ragunauth Ramsaroop

26 September 2026

Abstract

An independent evidence synthesis and audit-ready evaluation protocol for protected forests, causal climate benefits, Guyana reference-level accounting, rights and forest finance. Expanded second edition.



Original cover illustration: layers of forest canopy representing the relationship between existing forest carbon and monitored landscape change.

INDEPENDENT RESEARCH | FOREST CARBON | CONSERVATION GOVERNANCE

Publication statement

Author: Ragunauth Ramsaroop
Publication type: Independent research white paper; secondary evidence synthesis and methodological framework
Release: Version 2.0, 26 September 2026
Location: Georgetown, Guyana
Rights: © 2026 Ragunauth Ramsaroop. All rights reserved.
Contact: ragunauthramsaroop.com

This independent paper was prompted by Conservation International's public explanation of a 2023 scientific study. All interpretations, original analytical frameworks, illustrative models and policy options presented here are independent. Conservation International, the study authors, the Guyana government and the institutions cited did not sponsor, commission, review or endorse this publication. No claim of original satellite-data reanalysis or independent peer review is made. The source-derived tables are subject to their stated transcription and accounting boundaries. This expanded second edition adds a primary-source crosswalk for Guyana's UNFCCC 2025 assessment, an updated 320-study econometric meta-analysis, explicit audit tests, a new evidence matrix and a fully specified research design. It remains a secondary synthesis rather than a completed original spatial evaluation. Numerical results attributed to published studies retain their original dates, geographical coverage, assumptions and units. Readers should consult the underlying research and the cited primary data documentation when using results for regulatory submissions or financial transactions.

Citation suggestion: Ramsaroop, R. (2026). *Standing Forests, Measurable Outcomes: The Climate Value of Forest Protection, Governance and Carbon Accountability*. Independent white paper, version 2.0. Georgetown, Guyana.

Evidence cut-off: 26 September 2026. Publications, databases and standards change. Dataset versions and time periods appear beside all principal estimates.

Contents

Section	Page
Executive summary	4
1. Why standing forests require a different performance measure	6
2. How protected forests affect climate	8
3. What the global evidence demonstrates	9
4. Why comparison design determines credibility	13
5. A practical system for evaluating forest protection	14
6. Lessons from contrasting landscapes	17
7. Guyana as an application of the evidence	19
8. Climate finance and carbon-claim integrity	24
9. Climate, biodiversity and public reporting	26
10. The Forest Protection Performance Ledger	27
11. Scenarios, uncertainties and decision uses	29
12. Institutional implementation options	30
13. Research gaps and next tests	32
Closing assessment	32
Appendix A. Reproducibility	34
Appendix B. Carbon calculations	37
Appendix C. Audit checklist	38
Appendix D. Deep research and Guyana accounting	40
Appendix E. Evaluation design and data controls	42
References and source register	44

Executive summary

Protecting a forest preserves a standing stock of carbon, but designation alone does not establish how much climate benefit occurred because the forest was protected. The difference matters for national planning, biodiversity strategies, conservation investment, corporate sustainability reporting and carbon-credit claims. A carbon inventory answers where carbon exists. A counterfactual analysis asks what likely would have happened in the absence of protection. A credible climate-finance claim needs still more evidence: suitable baselines, demonstrated additionality, quantified leakage, durability provisions, safeguards and independent verification.

In 2023, Duncanson and colleagues used approximately 412 million observations from NASA's Global Ecosystem Dynamics Investigation (GEDI) and statistical matching to examine the carbon effectiveness of protected areas. Within the satellite mission's approximate 52 degrees north to 52 degrees south coverage, the researchers estimated 61.43 ± 0.31 billion tonnes of protected-area aboveground carbon and 9.65 ± 0.88 billion tonnes of additional carbon associated with protected status. Protected areas held, on average, 28% more aboveground carbon than their ecologically matched unprotected comparators. These are the study's estimates, not new measurements generated for this white paper [1].

The distinction between total stock and attributed difference changes the interpretation. Approximately 84% of the estimated protected-area aboveground carbon stock in the study was not assigned to protection as an incremental effect. The 9.65-billion-tonne estimate represents a model-based comparison of standing aboveground carbon. An equivalent carbon-dioxide mass conversion is approximately 35.4 billion tonnes CO2, but such a conversion does not establish an annual emissions flow, a sellable credit quantity or an additional atmospheric removal. Statistical uncertainty of ±0.88 billion tonnes C does not encompass every source of systematic uncertainty, including unobserved placement factors and possible leakage [1].

Global forest pressure has continued. FAO's Global Forest Resources Assessment 2025 estimates 4.14 billion hectares of forests worldwide, representing about 32% of land. Annual deforestation averaged 10.9 million hectares during 2015–2025, even as the rate slowed relative to preceding periods. Its distinct measure of net forest loss averaged 4.12 million hectares annually in the same decade. More than one fifth of forests fall within legally established protected areas under FAO's national reporting [2]. These FAO totals should not be conflated with the spatial domain, definitions or protected-area sample of Duncanson and colleagues.

The broader literature presents a consistent but qualified picture. Statistical studies identify important climate and habitat benefits in many protected tropical forests, while outcomes vary by location, ecosystem, management, external pressure, rights arrangements and analytical method [1, 3–8]. Indigenous territories and locally governed forests deserve explicit treatment. Research comparing matched tropical areas identifies lower deforestation and degradation in many Indigenous lands, while recording regional variation and interactions between formal designation and Indigenous governance [7, 8]. Formal protected-area coverage alone is an inadequate proxy for ecological condition or institutional legitimacy.

The practical finding of this review is methodological. A credible assessment should report five separate accounts: the total carbon currently stored; observed annual forest loss; the counterfactual difference associated with protection; the risk-adjusted durability of any attributed benefit; and conservation outcomes beyond carbon. The updated Forest Protection Performance Ledger, introduced in this paper, holds these accounts separately. Such separation helps prevent overstatement, supports independent audit and enables comparison without treating a hectare designated on paper as equivalent to a hectare with demonstrated ecological outcomes.

For Guyana, the distinction has immediate analytical value. National jurisdictional forest-carbon accounting under the Architecture for REDD+ Transactions and site-level performance monitoring address different questions. Guyana's Protected Areas Commission identifies distinct management arrangements and ecosystems across Kaieteur, Kanuku Mountains, Shell Beach, Iwokrama and the Kanashen Amerindian Protected Area. An independent site-level assessment should integrate protected-area boundaries, national forest-monitoring records, community evidence, aboveground biomass measurements and pre-specified comparison areas. Such work should avoid adding site-level estimates to already-accounted national credits or assigning newly calculated carbon-credit revenue without a corresponding registry and accounting basis [9–12].

This second edition offers an independent synthesis, a detailed implementation framework, contrasting international case studies, transparent worked examples, a finance-integrity checklist and a reproducibility roadmap. It does not claim a new global causal estimate or a certified carbon asset. Those outputs require registered research protocols, approved data access, actual geospatial processing, statistical diagnostics and independent review.

Second-edition evidence update. UNFCCC's November 2025 technical assessment of Guyana's revised reference-level submission materially changed the accounting presentation: an original annual forest reference level of 141,860,359 t CO2e was modified into an assessed emissions FREL of 32,695,707 t CO2e/year and a distinct removals FRL of -68,113,829 t CO2e/year. These are alternative accounting presentations, not sequential annual emissions observations. The assessment described the submission as transparent, complete and overall in accordance with applicable guidelines, while identifying areas for future technical improvement [29, 30]. For readers evaluating Guyana's forest finance, this change makes a source-specific distinction between national inventories, UNFCCC reference levels, local protected-area effects and ART registry credits essential. The 2023 updated meta-analysis of 320 peer-reviewed spatial econometric studies likewise reinforces the need to evaluate accessibility, agricultural returns, legal protection, forest enforcement and local governance together rather than regard protected status as a self-sufficient causal explanation [31].

What the evidence supports and does not support. The measured global protected-area standing-carbon difference in Duncanson et al. supports a substantial positive association after ecological matching, with assumptions and geographic limits. It does not demonstrate that 35.38 Gt CO2 of annual emissions have been avoided or that the same number of tradable credits exists. Guyana's official revised reference levels provide a national performance benchmark under the specified UNFCCC process; they do not measure site-specific protected-area additionality or the cash value of individual forests. The research protocol and sample data architecture in this edition are presented as reproducible specifications, not outputs from a completed GEDI reanalysis [1, 29, 31].

Five principal findings

One. Carbon stock and causal impact are different quantities. A forest might remain intact because of accessibility, terrain, land tenure, low economic pressure or local management rather than formal protection alone. Matching reduces observable differences but does not eliminate unmeasured confounding.

Two. The climate contribution of protection varies substantially. The 2023 study reports strong aggregate aboveground-carbon differences, with tropical moist forests and Brazil contributing a major share. It also identifies protected areas with little observed additionality and others with lower carbon than matched unprotected areas [1].

Three. Forest degradation matters alongside clearing. Selective logging and structural losses reduce forest carbon even where an optical satellite continues to classify a pixel as forest. Lidar, repeated biomass products and well-designed field inventories provide complementary evidence.

Four. Climate value has multiple risk dimensions. Displaced clearing, fire, drought, weak tenure, management gaps, insecure funding and carbon-accounting overlap all affect attribution and durability. These risks belong in results tables rather than in small-print disclaimers.

Five. A credible monitoring system separates observation from interpretation. Remote-sensing measurements, a defensible counterfactual, verified governance information and an auditable data history perform different roles. None should substitute for the others.

1. Why standing forests require a different performance measure

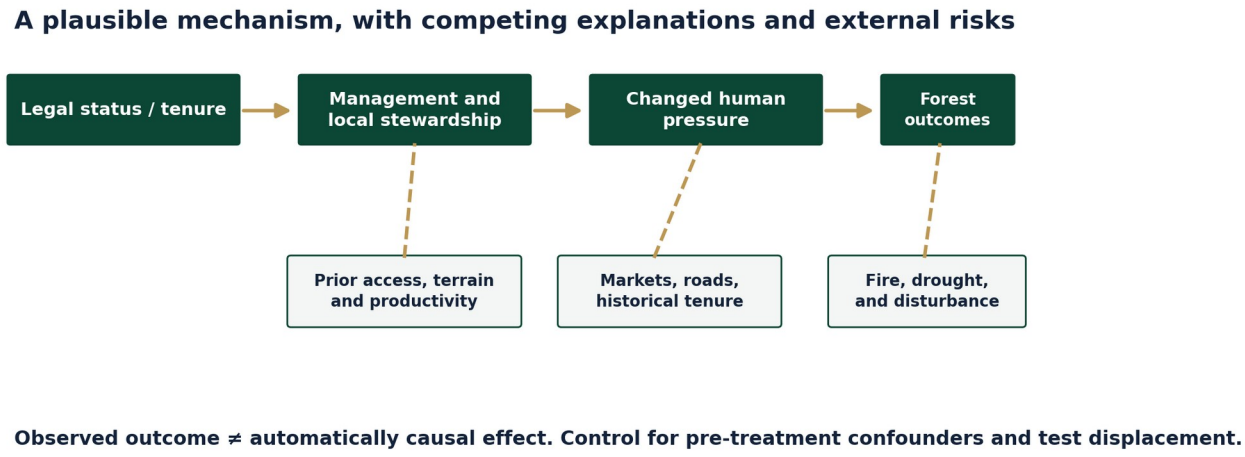


Figure 1. An original conceptual model of forest-protection mechanisms, confounding and climate risk. Dotted links represent potential competing explanations, not measured effects.

The public conversation about forest conservation frequently moves between four claims as if they were interchangeable: a country has extensive forest cover; a protected area stores considerable carbon; a reserve has avoided deforestation; and a conservation intervention has generated additional greenhouse-gas benefits. Each describes a different proposition. A national forest map supplies extent, a biomass model estimates carbon, a historical loss series shows observed change, and a counterfactual design attempts to attribute a difference to a particular intervention.

The central proposition of this paper is therefore narrower than a general endorsement of protected areas. Formal protection represents a potentially important institutional mechanism for retaining forest carbon, especially where credible conversion pressure exists. Its measured climate effect depends on what the protected landscape would otherwise have experienced, on the stability of management outcomes, and on the carbon pools included in the assessment. Evidence from a humid tropical reserve should not be transferred automatically to peatland, boreal forest, dry woodland or low-stature mangrove ecosystems.

A useful illustration concerns two forests, each holding one million tonnes of aboveground carbon. The first faces immediate road expansion and agricultural conversion. The second lies in a remote location without documented commercial pressure. Their current stock is identical, but the additional climate impact of a new conservation intervention may differ substantially. The calculation changes again if the first intervention displaces clearing to the adjacent district, or if the second forest contains major cultural and biodiversity values unrelated to near-term emissions reduction. A sound decision record treats these attributes separately.

This paper uses a three-layer evidence model. The first layer is **descriptive inventory**: land cover, legal boundaries, vegetation structure, carbon stocks and observed change. The second is **quasi-causal evaluation**: matched controls, pre-intervention trends and alternative counterfactuals. The third is **implementation integrity**: governance, safeguards, financing, leakage, reversals, public disclosure and conflict checks. The analytical standard rises from one layer to the next. An accurate biomass map does not establish effective governance; a positive matching result does not independently verify a tradable carbon credit.

The research question is: under which ecological, economic and governance conditions does formal forest protection deliver measurable additional climate value, and what monitoring and financial-accounting rules preserve the credibility of that value? This white paper evaluates published evidence through 25 September 2026 and proposes a practical framework rather than asserting a newly estimated global result.

1.1 Scope and exclusions

The primary stock metric is aboveground woody carbon in tonnes of carbon (t C), with biomass density measured in tonnes of dry biomass per hectare (Mg biomass/ha). When published sources use carbon-dioxide equivalents, the conversion factor and assumptions are reported explicitly. Forest soil, belowground roots, deadwood and litter are considered important but remain outside the 2023 study's principal global stock estimate. Wetland and mangrove applications therefore require separate accounting rather than extending the study's headline figure across all pools.

The geographic focus is global evidence within each source's stated coverage, with contrasting tropical case studies and a dedicated Guyana application. The policy discussion addresses international climate and biodiversity frameworks, national monitoring choices, and project-finance safeguards. It does not estimate the market price of forest carbon, claim ownership of forest resources or attribute new credits to any named protected area.

2. How protected forests affect climate

2.1 A stock, a flow and a counterfactual

Carbon enters forests through photosynthesis and accumulates in living wood, roots, soils and other pools. Forest respiration, decomposition, fire, harvest and land conversion release carbon. A stock is the quantity present at a given time. A flow is the quantity entering or leaving during a stated period. A protected-area evaluation needs to record both, but should not replace one with the other. A single satellite snapshot of high carbon density cannot demonstrate annual net sequestration.

The *retained stock* associated with protection is a difference between observed carbon at a measurement date and the estimated amount expected under a credible unprotected comparison. The term *avoided emissions* applies when the counterfactual difference is attributable to reductions in losses that otherwise would have transferred carbon to the atmosphere. Enhanced forest growth, delayed harvest, shifting emissions among pools and changing wood-product storage complicate the translation from a standing-carbon difference into atmospheric emissions. Time, geographic domain and the fate of disturbed biomass are therefore material components of the estimate.

2.2 Two routes to a positive carbon difference

Protection might prevent complete stand replacement, such as clearing for agriculture. Alternatively, protection might limit partial degradation while maintaining the forest canopy. A third mechanism involves enhanced recovery after previous disturbance. These processes leave different remote-sensing signatures. A tree-cover-loss algorithm detects conspicuous canopy removal, whereas repeated lidar, radar or field biomass measurements address structure and density. A positive carbon gap between protected and unprotected sites with little difference in mapped canopy loss is consistent with avoided degradation or growth. Without repeated direct measurement and causal analysis, the relative contributions remain uncertain.

The Duncanson study used observed differences in forest structure, carbon density and historical tree-cover loss to investigate these routes. Its matched comparison supports an attribution to protected status under the authors' assumptions. The result is stronger than an unadjusted inside-versus-outside comparison, but the assumption of comparable earlier carbon stocks is not directly observed for every pixel [1].

2.3 Non-carbon climate functions

Forests also influence energy exchange, evapotranspiration, local temperature, moisture transport and fire regimes. Tropical forest loss affects regional rainfall and local heat in ways not fully described by aboveground carbon alone. Carbon maximisation is therefore not equivalent to maximising all climate or biodiversity outcomes. Conversely, a habitat with modest aboveground carbon might hold high ecological value, store substantial soil carbon or support indispensable freshwater functions. An accounting system focused solely on woody carbon would overlook such outcomes.

2.4 Temporal integrity

Protected forests face changing climate, wildfire regimes, pests and economic pressures. A positive stock difference measured over an earlier period is not a guarantee of future storage. Risk

statements should separate physical reversal from changes in legal designation, community consent, finance continuity and measurement uncertainty. The appropriate reporting horizon depends on the purpose: ecological management, national inventory, public expenditure evaluation or carbon-credit issuance. These purposes should not be compressed into a single undifferentiated carbon number.

3. What the global evidence demonstrates

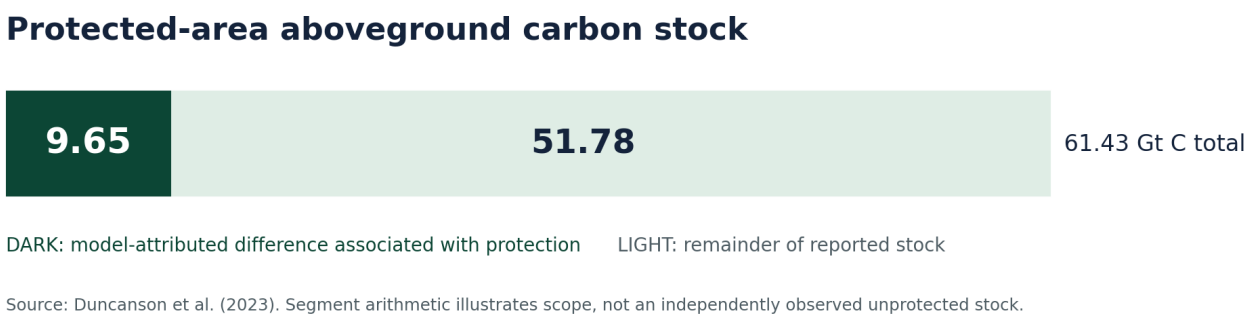


Figure 2. The published protected-area stock and matched, protection-associated increment in Duncanson et al. (2023), both in Gt C. The pale segment is arithmetic, not a separately measured forest class.

3.1 The 2023 GEDI study

Duncanson and colleagues examined protected areas using approximately 412 million GEDI lidar observations, matched one-kilometre protected-area pixels with ecologically similar unprotected pixels and analysed canopy structure and aboveground carbon around 2020. The matching design incorporated climate, ecological category, country, land-cover characteristics and human-pressure variables representing conditions around 2000. A ten-kilometre exclusion zone around protected-area boundaries helped reduce mixed-pixel and immediate spillover complications. Pixels fully inside protection boundaries formed the principal treatment sample [1].

The study reported 61.43 ± 0.31 Gt C in protected-area aboveground woody vegetation across its observational domain. Its published estimate of additionally preserved carbon associated with protected status was 9.65 ± 0.88 Gt C. Protected sites averaged 28% higher aboveground carbon than matched comparators, and approximately 62.7% of analysed forested protected areas showed significantly higher carbon than their matching controls [1]. The authors also found negative and near-zero site-level outcomes, a reminder to avoid inferring that every protected designation delivered a measurable carbon increment.

The GEDI mission observes between approximately 52 degrees north and south. The study's domain omits much of the northern boreal zone and does not supply repeated global biomass observations for every year since 2000. The analysis inferred a historical protection effect by pairing year-2000 covariates with later structure observations and the Landsat forest-loss record. It did not track every tree's carbon balance from 2000 to 2020 [1, 13].

3.2 Quantities that should not be conflated

Published metric	Reported value	Interpretation	Principal boundary
Protected-area aboveground carbon stock	61.43 ± 0.31 Gt C	Woody carbon located inside sampled protected areas	GEDI observational domain [1]
Additional carbon associated with protection	9.65 ± 0.88 Gt C	Estimated difference from matched unprotected counterfactuals	Dependent on matching and attribution assumptions [1]
Mean matched aboveground-carbon difference	28%	Average relative difference in the analysed comparison	Not a universal site-specific rate [1]
Forested protected areas with higher carbon	62.7%	Share of studied forested protected areas with significant positive difference	Site-level heterogeneity [1]
Global forest area in FAO FRA 2025	4.14 billion ha	Officially reported forest extent	Different definitions and global population [2]
Average annual deforestation, 2015–2025	10.9 million ha	Gross permanent forest conversion rate in FRA	Not equivalent to annual Hansen tree-cover loss [2, 14]

The reported uncertainty of ±0.31 Gt for total stock and ±0.88 Gt for associated additional stock reflects uncertainty as estimated by the source study. It should not be presented as exhaustive uncertainty across biomass-model bias, protected-area boundary errors, imperfect counterfactual comparability, baseline differences or political and ecological changes after observation. These additional uncertainties call for separate stress tests.

3.3 Implications for interpretation

A large protected-area stock establishes the importance of existing carbon assets. The smaller attributed difference estimates the additional aboveground stock associated with protection under the published model. Neither amount should be counted as a newly issued carbon-credit volume. The global estimate contains existing and historically retained carbon, covers an extended observation interval and excludes important pools. A crediting standard instead specifies its own eligible jurisdiction or project, baseline, vintage, leakage treatment, permanence requirements and accounting controls.

The article prompting this paper summarised the peer-reviewed findings for a wider audience [15]. This white paper relies on the underlying study for scientific statements and uses other research to evaluate limitations. It does not reproduce the article's narrative or graphics.

3.4 Evidence beyond one global study

Earlier work on Brazilian Amazon protected areas modelled the role of the protected-area system in reducing future deforestation and preserving associated carbon, but its scenario results depend on

assumptions about policy, land-use pressure and enforcement [4]. Tropical forest studies using matched controls and quasi-experimental methods have estimated meaningful reductions in loss attributable to protection in various regions, while documenting weaker outcomes elsewhere [3, 5, 6]. The precise effect depends on site selection, a clear definition of treatment, forest pressure and the reference period.

A 2013 systematic review of protected-area outcomes found evidence of reduced habitat loss in many settings but identified limitations in comparative evidence and major variation in management and monitoring [3]. Comparative research into human pressure and forest integrity likewise supports assessing real ecological performance rather than the administrative count of protected hectares [6, 8]. A global average obscures the distribution: large benefits in high-pressure forests can coexist with negligible short-term additionality in remote sites and negative effects in poorly governed locations.

3.5 Indigenous and community-governed forests

Legal designation is not synonymous with effective stewardship, and government-managed conservation is not the only governance arrangement. A pan-tropical analysis of Indigenous Lands, protected areas and overlapping Indigenous-protected landscapes during roughly 2010–2018 found reduced deforestation in Indigenous Lands relative to matched non-protected comparators, along with broadly comparable reductions in degradation under several regional comparisons [7]. A separate study of tropical forest integrity identified strong outcomes in overlapping protected-Indigenous areas while also finding regional differences between land-governance categories [8]. Recent research on Apurinã territories in southwestern Amazonia links avoidance of deforestation to institutional, historical and community-level conditions rather than a one-size-fits-all legal designation [16].

These findings warrant careful treatment. Different studies employ different territory definitions, counterfactuals, outcomes and sample periods. None establishes that a single governance model consistently outperforms every other arrangement at every site. Indigenous rights, land tenure, consent, livelihoods and locally defined stewardship objectives are substantive governance issues, not merely explanatory variables in a statistical model. Public conservation reporting should make those distinctions visible.

3.6 New comparative evidence: 320 spatial econometric studies

Busch and Ferretti-Gallon's updated 2023 meta-analysis encompasses 320 peer-reviewed spatial econometric studies published from 1996 to 2019. It associates greater deforestation with accessibility and economic returns from agriculture, livestock and timber; it associates forest-protection policies, enforcement, payment for ecosystem services, community forest management and relevant certification schemes with lower forest loss in many settings. Its synthesis also reports variables with inconsistent relationships. This literature is wider than the protected-area treatment in the GEDI study: it assesses multiple policy mechanisms and often uses forest loss rather than aboveground carbon as the outcome. Its coefficients cannot be pooled naively with the 9.65 Gt C matched global stock difference [31].

An independent review should distinguish three questions: whether forest-loss pressure changed inside a designated area, whether that change was caused by protection rather than initial placement, and whether the difference translated into atmospheric benefit after carbon-pool

accounting and displacement. The first question may be answered with descriptive remote-sensing data; the second requires an identification strategy; the third additionally requires emissions factors, timing, permanence and a defined geographical accounting boundary. No single remote-sensing layer answers all three.

Nolte and colleagues' 2013 study examined 292 protected areas in the Brazilian Amazon, testing governance and location under differing levels of deforestation pressure. Their findings emphasize heterogeneity: all studied protection regimes reduced deforestation, but the relationship of strict protection, sustainable use and Indigenous lands to forest-loss pressure differed. The result is geographically and historically bounded, and it neither establishes a universal governance ordering nor eliminates potential unobserved confounding [32]. Related evidence from Acre illustrates why different allocation of protection regimes across high- and low-pressure land can alter an apparent comparison [33].

Evidence	Design and observation	Outcome	Principal inference	Scope restriction
Duncanson et al. [1]	Global GEDI lidar and ecological matching, ~412 million observations	Aboveground woody carbon stock	9.65 ± 0.88 Gt C estimated protection-associated difference; matched protected area +28% mean	Spatial sampling and residual selection; not annual credits
Busch & Ferretti-Gallon [31]	Meta-analysis of 320 spatial econometric studies, 1996-2019 publications	Forest loss, reforestation and degradation	Accessibility and economic pressure matter alongside conservation policies	Synthesis of heterogeneous studies; no global Gt C estimate
Nolte et al. [32]	292 Brazilian Amazon protected areas and matched comparisons	Avoided deforestation	Regime, location and pressure jointly shape outcomes	One biome and historical policy contexts
Sze et al. [7, 8]	Pan-tropical comparative analyses of Indigenous lands and protected categories	Deforestation, degradation and integrity	Many Indigenous territories show strong stewardship outcomes	Definitions, comparison sets and tenure differ by country
FAO FRA 2025 [2]	Nationally reported forest statistics	Area and change	Contextual trend and official reporting baseline	Not a causal protected-area evaluation

Evidence-quality note: The effect estimates above describe different estimands. The table deliberately does not present a pooled 'global effect size' from incompatible study populations or measurements. A systematic quantitative meta-analysis would require effect extraction and a preregistered synthesis protocol beyond the scope of this paper.

4. Why comparison design determines credibility

4.1 The protected-area placement problem

Authorities often establish protected areas in places with unusual terrain, lower agricultural suitability, limited road access or lower pre-existing commercial demand. A simple average comparing carbon inside all protected sites with carbon outside would mix selection effects with protection effects. Remote high-altitude reserves may have remained forested even without a legal designation. Accessible lowland reserves may face much greater conversion pressure. The relevant question is what each protected site would have experienced under a credible alternative institutional arrangement.

Statistical matching addresses observed placement differences by comparing sites with similar pre-treatment characteristics. Exact matches on country, biome and ecological region restrict comparisons to broadly similar contexts. Matching on baseline forest cover, elevation, slope, rainfall, distance to transport networks and earlier human pressure further improves comparability. Balance diagnostics should demonstrate the remaining differences rather than assume they are immaterial.

4.2 The unobserved-variable problem

Matching does not prove that protected and unprotected locations were otherwise identical. Historical tenure, local political arrangements, conflict, conservation support, customary restrictions, corruption exposure and anticipated infrastructure development might differ despite similar mapped covariates. Results should acknowledge possible residual selection bias. Where designation dates and sufficient pre-designation observations exist, difference-in-differences, event studies and boundary-based comparisons offer complementary tests. Each method has its own assumptions and failure modes.

4.3 Treating the baseline as a historical claim

If a reserve received protected status before the remote-sensing baseline, a year-2000 match cannot erase previous protection effects or fully identify the no-protection condition before designation. A comparison performed decades after establishment also faces selective survival, land-use spillovers and historical disturbances. For newly established protected areas, analysts should record the exact designation date, legal status, boundary changes, previous local interventions and data availability. A pre-specified study protocol should state whether the target is the impact of initial designation, subsequent management or a broader conservation regime.

4.4 Spatial dependence and leakage

Forest-loss observations cluster along roads, property boundaries and agricultural frontiers. Statistical confidence intervals should address spatial dependence instead of treating neighbouring

pixels as independent experiments. Leakage adds a separate attribution challenge: reduced loss inside a reserve might accompany greater loss immediately outside, or within a wider market and transport region. A boundary buffer removes contaminated control candidates but does not demonstrate that the displaced activity never occurred. Analysts should evaluate forest-loss rates in multiple distance bands and, where credible, at regional market scale.

4.5 An evidence hierarchy for this paper

Evidence level	What it establishes	What it does not establish
Verified boundary and land-cover map	Designated area and observed vegetation cover	Carbon stock, management quality or causal effect
Field-calibrated biomass inventory	Estimated carbon stock in defined pools	Counterfactual additionality
Multi-year change detection	Observed canopy loss or biomass change	Attribution without appropriate controls
Matched quasi-experimental comparison	Difference associated with protection under specified assumptions	Elimination of all unobserved bias or leakage
Repeated counterfactual and leakage analysis	More robust attribution over time	Permanent climate benefit
Standard-specific verification and registry reconciliation	Conformity with a defined crediting framework	Universal equivalence across standards or legal title

The review treats these levels as complementary rather than interchangeable. The target is a transparent chain of evidence, from mapped observation through inference to any external claim.

5. A practical system for evaluating forest protection

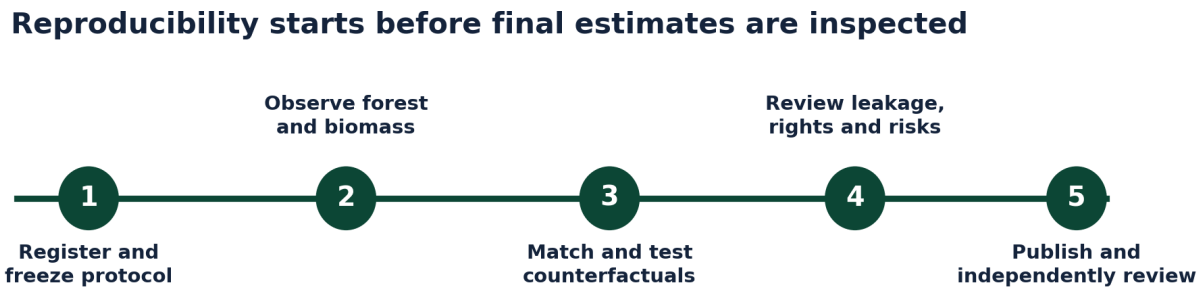


Figure 3. Reproducible evaluation sequence. Independent interpretation begins with a frozen protocol rather than a preferred effect size.

This section translates the literature into a replicable evaluation design. The proposed approach is a protocol, not an assertion that the analyses have already been run. Research teams should freeze the protocol before viewing final effect estimates, identify each eligible source dataset, register exclusions and publish machine-readable diagnostics. The preferred analytical sequence is

descriptive inventory, matched comparison, temporal validation, leakage tests, biomass sensitivity analysis and governance interpretation.

5.1 Define the intervention before collecting outcomes

A protected area's boundary is a geographic statement. The treatment definition must also specify legal status, date of effect, management arrangement and qualifying conservation activity. For a conventional protected-area study, each treatment pixel should lie completely inside a valid protected polygon and meet baseline eligibility criteria. Analysts should dissolve overlapping designations for area and stock accounting, while retaining the original designations as separate governance attributes. A reserve that changed boundaries or management authority needs a traceable event history.

Other Effective Area-Based Conservation Measures, Indigenous territories, privately conserved lands and community-managed landscapes should appear in separate analytical strata when consistent legal and spatial data exist. Combining them without recording governance form prevents a meaningful interpretation of differences. At the same time, excluding all such territories from conservation accounting would hide consequential stewardship and landscape connectivity.

5.2 Construct the reference period and controls

For a global retrospective study, a year-2000 baseline aligns with the historical Hansen forest-cover product. Yet a protected area designated after 2000 and one established in 1929 have different exposure histories. A modern protocol should group sites by designation period and run pre-designation designs where satellite history permits. The preferred control pool should exclude designated protection, overlapping conservation arrangements and immediate boundary-contamination zones, while preserving comparability within country and ecosystem.

Use exact matching on country, biome, ecological region and broad pre-treatment cover class. Within the resulting strata, use a transparent distance or propensity-based match for elevation, slope, climatic normals, baseline tree cover, distances to roads and settlements, and pre-treatment human pressure. Record exclusions where equivalent controls are unavailable. Report standardised mean differences before and after matching, overlap distributions, matched-sample retention and regional sample weights. Publish both site-level and area-weighted estimates where data rights permit.

5.3 Outcome variables

The primary ecological outcomes should remain separate. Gross tree-cover loss captures stand-replacement disturbance. Biomass carbon density captures standing aboveground carbon. Forest structure adds canopy height and vertical complexity. Forest integrity addresses fragmentation, human modification and spatial context. A national assessment might add forest degradation, soil carbon, peat, fire severity and livelihood indicators. Combining all outcomes into one undocumented index would remove the distinctions essential to causal interpretation.

Outcome	Suggested unit	Preferred evidence	Major interpretive constraint
Baseline forest extent	hectares	Historical optical imagery and national maps	Forest definition and canopy threshold
Annual gross tree-cover loss	hectares/year	Hansen GFC v1.13 and national products	Includes temporary loss and plantations
Aboveground biomass density	Mg dry biomass/ha	GEDI L4A/L4B, ESA CCI and plots	Model errors, temporal mismatch
Aboveground carbon stock	t C and t C/ha	Biomass times documented carbon fraction	Excludes other carbon pools
Matched protection-associated difference	t C/ha and total t C	Frozen counterfactual design	Residual selection bias
Detected degradation	hectares, severity and t C	Radar, lidar, targeted field measurements	Detectability and attribution
Leakage indicator	differential loss rate by zone	Protected boundaries and wider reference region	Market displacement beyond buffer
Reversal indicator	affected carbon by event and period	Fire, disturbance and field evidence	Attribution and recovery time
Rights and governance	documented status and qualitative findings	Public records and participatory verification	Incomplete disclosure and context

5.4 A reproducible six-stage workflow

Stage A, provenance. Register the protected-area database release, legal boundaries, national forest maps, carbon products, coordinates, projection, image acquisition dates, terms of use and the processing code version. Store checksums and a data dictionary. Do not place restricted raw Protected Planet geometry in a public code repository without permitted redistribution.

Stage B, harmonisation. Use an equal-area projection appropriate to the study region for area calculations. Preserve native resolution for raw observations, then create a documented common analysis grid. Mask permanent water, flag no-data cells and separately tag natural forest, plantations and mangroves where defensible datasets exist.

Stage C, statistical design. Construct treatment and candidate comparison locations according to a registered rule. Preserve designation dates and baseline covariates. Require a pre-specified minimum standard for covariate balance, and record any departures rather than dropping inconvenient sites without explanation.

Stage D, estimation. Calculate observed area and carbon outcomes, matched mean differences, area-weighted treatment estimates and appropriate clustered uncertainty. Conduct sensitivity tests using alternative match settings, forest thresholds, biomass products and exclusions.

Stage E, displacement and permanence. Test forest loss across near- and far-boundary zones, examine fire and drought exposure, assess reserve management continuity and evaluate whether aggregate pressure shifted to another administrative area. A null ring result does not rule out wider commodity-market leakage.

Stage F, interpretation and assurance. Reconcile national aggregates, seek local verification, examine rights and governance evidence, separate measured findings from scenarios and record independent review comments. A study intended for carbon-credit issuance must separately satisfy the relevant standard and registry requirements.

5.5 Monitoring frequency

Annual optical forest-loss reporting suits many national and conservation-agency uses, supplemented by event-triggered assessments after severe fire, major road development or boundary change. Biomass updates follow the observation schedule and uncertainty of the selected product, with field plots revisited according to ecosystem growth rates and the applicable inventory design. Governance and rights reviews require direct community engagement rather than satellite-only monitoring. Every new result should carry a date and a comparison with the same metric from the prior reporting period.

5.6 What counts as a sensitivity test

The protocol should quantify changes across at least four pre-specified alternatives: baseline canopy thresholds of 10%, 30% and 50%; exclusion buffers of 5, 10, 20 and 50 kilometres; GEDI and ESA biomass estimates for common dates and regions; and alternative matching or weighting specifications. A natural-forest-only sample should sit beside any all-tree-cover sample. Time trends should separate early and recent periods when sensor availability or detection methods changed. Publish failed or unstable models rather than presenting only the specification with the largest positive effect.

6. Lessons from contrasting landscapes

Global estimates are informative for aggregate accounting, but local relevance depends on ecological setting, historical pressure and governance. Four international settings offer complementary tests of the mechanisms described above. These sections synthesise published evidence and propose analytical applications. They do not assert new case-study effect sizes.

6.1 Brazilian Amazon: high-carbon forests under heterogeneous pressure

The Brazilian Amazon combines extensive humid tropical forests with pronounced differences in road access, agricultural profitability, land tenure and historical enforcement. Duncanson and colleagues reported the largest regional contribution to their additional aboveground-carbon estimate in Brazil, broadly consistent with the importance of high-carbon ecosystems exposed to substantial conversion pressure [1]. Earlier research by Soares-Filho and colleagues modelled the contribution of Brazilian Amazon protected areas to avoided deforestation and potential emissions mitigation. Its scenario-based findings demonstrate why institutions and projected economic pressure belong in the causal account [4].

A Brazilian replication should stratify reserves by designation period, land tenure, road-frontier location, existing clearing and biome. Cross-check satellite forest loss against Brazil's national PRODES system while preserving each product's definition of deforestation. A global 30-metre tree-cover-loss series and a national legal deforestation monitor do not classify every disturbance identically. Cross-system agreement supports confidence, while disagreement may reflect different vegetation classes, thresholds, timing or measurement units.

The research significance of Brazil lies in heterogeneity. A site established along an agricultural frontier faces a different counterfactual from a remote reserve protected long before the satellite baseline. A comprehensive evaluation should show both outcomes rather than relying solely on the country's aggregate contribution to a global carbon estimate.

6.2 Indonesia and Malaysia: mangroves expose measurement limits

Mangroves store carbon in woody biomass, belowground roots and often substantial wetland soils. A framework centred on aboveground woody carbon therefore undercounts a defining part of the ecosystem. Duncanson and colleagues found a weak aggregate mangrove signal and lower protected-area aboveground carbon than matched sites in some Indonesian and Malaysian comparisons, while noting possible explanations involving tree stature, legacy disturbance and management conditions [1]. Published studies of mangrove protection also report reduced losses in specific settings, so a negative aboveground-carbon difference should not be interpreted as proof of zero conservation value.

A mangrove protocol needs a mangrove-specific extent mask, appropriate biomass relationships, coastline migration analysis and explicit treatment of peat or sediment carbon where data are available. It should account for shrimp aquaculture, road development, altered freshwater flows and coastal erosion. Rapid changes in shoreline geometry create boundary and baseline problems absent from many upland forest studies. Separating carbon pools and coastal processes improves both research validity and public understanding.

6.3 Congo Basin: high standing stocks and changing access

Central African forests hold extensive carbon assets and include landscapes with historically lower clearing pressure than parts of the Amazon or Southeast Asia. Remote location might produce strong standing stocks alongside a smaller measured short-term additional effect. Conversely, a reserve near expanding roads, mining corridors or settlement pressure might show a consequential counterfactual difference despite similar present-day carbon density. The distinction illustrates why future threat scenarios and retrospectively measured additionality answer different questions.

For the Democratic Republic of the Congo and neighbouring countries, combine protected-area geometry, baseline access measures, annual loss, biomass and any available local enforcement records. Stratify by forest type and pre-existing accessibility. Report whether matched comparison sites share a common governance and economic setting. Where maps omit informal roads or customary tenure, state the unobserved-confounder risk. Do not infer the causal impact of individual mining concessions or infrastructure projects without an event-specific study.

6.4 East African woody ecosystems: avoiding a rainforest-only framework

Dry forests, miombo woodlands and savannas differ from humid tropical forests in biomass density, fire regimes, seasonal leaf cover and the role of grazing. Lower aboveground woody carbon does not imply lower biodiversity or livelihood value. Duncanson and colleagues reported important protection-associated carbon differences in African non-forest-dominated biomes, highlighting the danger of defining all ecological success through dense-canopy metrics [1].

An East African case study should separate woody biomass from grass and soil carbon, distinguish anthropogenic clearing from periodic fire, and test appropriate seasonal observations. A uniform tree-cover threshold may classify ecologically important woodland as non-forest. Any comparison should account for variation in legal grazing rules, community rights, controlled burns and fuelwood dependence. An intervention suited to a humid tropical reserve may produce different ecological tradeoffs in pastoral landscapes.

6.5 Cross-case synthesis

Landscape	Main analytical mechanism	Important omitted variable	Appropriate extension
Brazilian Amazon	Avoided conversion under strong spatially varying pressure	Frontier enforcement and tenure history	National loss-data comparison and event studies
Southeast Asian mangroves	Aboveground carbon versus total blue-carbon system	Soil carbon and shoreline mobility	Mangrove-specific field and sediment monitoring
Congo Basin	Large stocks under uneven emerging pressure	Informal access, future road construction	Pressure stratification and longitudinal access maps
East African woodland	Fire, grazing and lower-stature woody carbon	Seasonal dynamics and ecosystem heterogeneity	Biome-specific structural and soil measurements

These cases do not form an effectiveness ranking. Each reveals a different reason to qualify global average results. A future global replication should freeze the case portfolio before inspecting country-level effect estimates to reduce selective presentation.

7. Guyana as an application of the evidence

Guyana provides a relevant setting for linking forest measurement, conservation governance and jurisdictional climate finance. The country has high forest cover, documented protected areas with different management arrangements, an established national forest monitoring system and national-level issuance of jurisdictional forest-carbon credits. These institutions address related but distinct accounting questions [9–12]. The discussion below provides an independent analytical application rather than a claim of new carbon measurements for Guyana’s reserves.

7.1 Distinguish the national account from protected-area performance

Guyana's Monitoring, Reporting and Verification System (MRVS), operated through the Guyana Forestry Commission, reports national forest-cover change, drivers of deforestation and degradation, and forest-carbon emissions and removals. Its 2023 assessment report records a long-running monitoring programme established after the 2009 national roadmap, with methodological development over subsequent phases [10]. National accounting estimates a jurisdiction-wide result under defined rules and reference periods. A site-level evaluation of an individual reserve instead tests the association between that site's conservation arrangement and ecological outcomes relative to a credible local counterfactual.

National jurisdictional issuance under ART's TREES standard is a third layer. A 2024 government announcement described 7.14 million 2021-vintage credits issued to Guyana and labelled eligible under the first phase of CORSIA after corresponding-adjustment arrangements [11]. Public national announcements and ART documentation should be reconciled against the official registry for any transaction-specific statement. A site-level retained-stock estimate must not be added to national-issued quantities as though the same atmospheric benefit occurred twice.

7.2 Five differentiated governance examples

Guyana's Protected Areas Commission lists the Shell Beach Protected Area, Kaieteur National Park, Kanuku Mountains Protected Area, Iwokrama and Kanashen Amerindian Protected Area as core elements of the national protected-area system. The Commission describes differing institutional responsibilities: direct management for several national areas, a separate governance framework for Iwokrama, and management of Kanashen by its Village Council with technical support from the Commission [9]. A rigorous assessment should record these differences before aggregating results.

Shell Beach. The Commission reports a roughly 123,055-hectare protected area declared in 2011, with a coastal mosaic of beaches, mangroves and inland swamp forest. Local community consultation formed part of establishment. A biomass-only headline would omit sediment carbon, coastal geomorphology, local resource use and the value of nesting habitat [9, 17]. The appropriate analytical unit includes coastal processes and mangrove-specific carbon pools.

Kaieteur. Founded in 1929 and later altered, Kaieteur National Park combines long-standing legal protection with a history of boundary revision. The Commission reports a current area of about 62,700 hectares [9, 18]. A year-2000 retrospective study would therefore evaluate the condition of an already protected landscape, not the full impact of original designation. Any historical claim should reconstruct the legal boundary in effect during each observation period.

Kanuku Mountains. This protected area, established in 2011 and reported at about 611,000 hectares by the Commission, spans dense forests and other habitats. Heterogeneity requires stratification by vegetation type, terrain and pre-designation accessibility [9]. A single average biomass value would conceal major ecological variation.

Iwokrama. The roughly 371,000-hectare forest has a distinctive international research and governance framework dating from 1996 [9]. Sustainable-use and research objectives should be represented as management characteristics, rather than assuming identical rules across all national protected areas. Any independent evaluation should distinguish legal designation from specific commercial and community arrangements.

Kanashen. The Kanashen Amerindian Protected Area, added to the national system in 2017, is managed by the Kanashen Village Council [9]. Its governance structure makes community-defined priorities, consent and data access fundamental parts of the evaluation design. Indigenous stewardship should not be represented as a secondary proxy for state enforcement.

The Protected Areas Commission's site descriptions provide administrative background, not causal estimates of forest-carbon effectiveness. The descriptions support a sampling strategy that includes contrasting ecosystems and governance structures. Published national totals, protected-area polygons, field inventories and community-verified histories should be reconciled before computing any new figures.

7.3 Suggested Guyana evaluation architecture

A first study package would freeze historical boundary versions, designation dates and governance information for the five sites. A second would intersect eligible pixels with the national forest-monitoring baseline and comparable unprotected landscapes. A third would attach GEDI or ESA biomass observations, land-cover change, road access, mining and agriculture pressure, climatic conditions and field-plot validation where permitted. All datasets should retain their native definitions and temporal coverage.

Where sufficient comparison data exist, pre-specify matched controls by ecosystem and baseline pressure. Kaieteur's long pre-2000 legal history requires a different inference statement from Kanashen's 2017 designation. Shell Beach requires mangrove-specific methods and coastal change controls. At Kanashen and Iwokrama, research protocols should reflect local institutional permissions and Indigenous or community rights. Present a separate results sheet for every site before calculating an aggregate national comparison.

The research question for each site is not whether the legal designation is commendable. The question is which observed carbon, forest-integrity, biodiversity and social outcomes are associated with the documented governance arrangement under a credible alternative. A robust paper should report uncertainty, absence of suitable controls and unobserved governance factors rather than supplying a single unqualified Guyana-wide number.

7.4 Forest finance without duplicate claims

An investor, public agency or conservation partner evaluating Guyana's protected forests should ask three different questions. First, what standing carbon and ecosystem services exist, regardless of crediting? Second, what additional effect can be attributed to a specific intervention under a documented counterfactual? Third, who holds rights to claims, revenue and registry instruments at national and site levels? Positive answers to the first two do not settle the third.

Under jurisdictional accounting, nested project treatment, transfer authorisation and double-counting safeguards require documentary reconciliation with the applicable programme and national authorising bodies. A new academic estimate of site-level additional carbon does not independently create a registered asset. Public financing can support monitoring, ecological management or community institutions without a carbon-credit issuance, while results-based finance requires its own eligibility and measurement rules.

7.5 A bounded Guyana research agenda

The five-site comparison provides a natural set of questions rather than a predetermined conclusion. Which sites show detectable reductions in gross tree-cover loss after controlling for terrain and access? Where does lidar indicate higher forest structure without a corresponding optical forest-loss difference? How do results change when road expansion, mining pressure and local rights records enter the model? Do coastal mangroves require separate treatment? Which national MRVS metrics reconcile with site-level observations, and where do differences reflect classification rules rather than performance?

Answering these questions would create an independent evidence base for conservation management, public reporting and academic publication. This paper supplies the protocol. No site-level effect estimate is asserted here.

7.6 The 2025 UNFCCC assessment changes the national benchmark

Guyana submitted its revised REDD+ reference-level proposal on 18 December 2024, using the historical reference period 2018-2022. The initial formulation was 141,860,359 t CO2e/year. Following the March 2025 technical assessment, the official November 2025 assessment reported two separately signed and interpreted quantities: 32,695,707 t CO2e/year for emissions from deforestation and degradation (including a national-circumstances adjustment), and -68,113,829 t CO2e/year for removals linked to conservation of forest carbon stocks and sustainable forest management [29, 30]. The change was not a real-world annual emissions reduction from 141.86 to 32.70 million tonnes. It is a revised accounting presentation with an explicitly negative removal quantity.

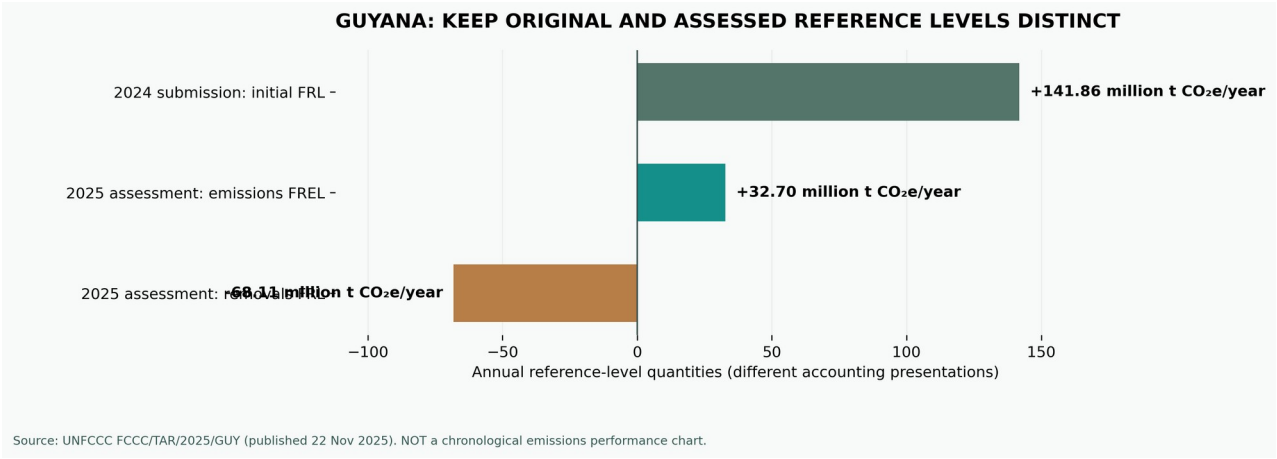


Figure 6. Accounting crosswalk for Guyana's initial and assessed annual REDD+ reference-level presentation. The initial combined value and the two later components are NOT consecutive monitoring years or a common performance series.

UNFCCC's assessment judged the data and information transparent, complete and overall aligned with applicable guidance, and documented opportunities for technical improvements [29]. That institutional assessment is important but is not equivalent to independent verification of site-level avoided emissions or automatic eligibility of a particular claimed credit volume. The paper's proposed Guyana reporting crosswalk therefore has four non-additive columns: *MRVS observed forest activity*, *UNFCCC national reference-level components*, *site-level causal protection evaluation*,

and *ART TREES serialized issuance and disposition*. Reconciliation belongs within each system before cross-system comparisons are attempted.

The December 2024 submission provides an official historical series. A distinct source-derived project table in the companion package transcribes approximate annual total forest emissions of 13.70, 17.19, 14.84, 11.95 and 10.69 million t CO2e for 2018, 2019, 2020, 2021 and 2022 respectively [30]. These historical figures must retain the submission's measurement and pool definitions; they must not be presented as the later assessed reference level or be described as independently estimated results. A future field study should reconcile transcription directly to the exact final submission and any subsequent published revisions before relying on exact annual values.

7.7 Forest finance, community allocation and contestable claims

Guyana and Hess publicly announced a ten-year arrangement covering 37.5 million ART TREES credits with a minimum value of US$750 million; official Guyana reporting subsequently described a US$75 million first payment and an allocation framework of 15% for village-led and community-led Indigenous and local-community programmes and 85% for broader national LCDS priorities [34, 35]. An announced long-term contract value is not the same as cash received, credits issued, credits transferred or credits retired. The ledger in this paper records all five separately, with vintage and source evidence attached. Each downstream claim should be checked against current public ART registry records, the actual agreement and corresponding national budget or disbursement records [36].

Rights and safeguards cannot be inferred from the existence of a registry entry. The Amerindian Peoples Association's 2023 ART grievance and the Government of Guyana's public response reflect documented disagreement regarding consultation and the assessment of community support. The ART complaints and appeals record, the underlying complainants' submissions, the government response and independently documented consent and benefit-distribution evidence should be reviewed together. This white paper does not independently decide disputed representational claims [37, 38]. Site-level research must seek the appropriate community approval, provide accessible notice of planned data collection, and ensure that public maps do not expose culturally sensitive spatial information without permission.

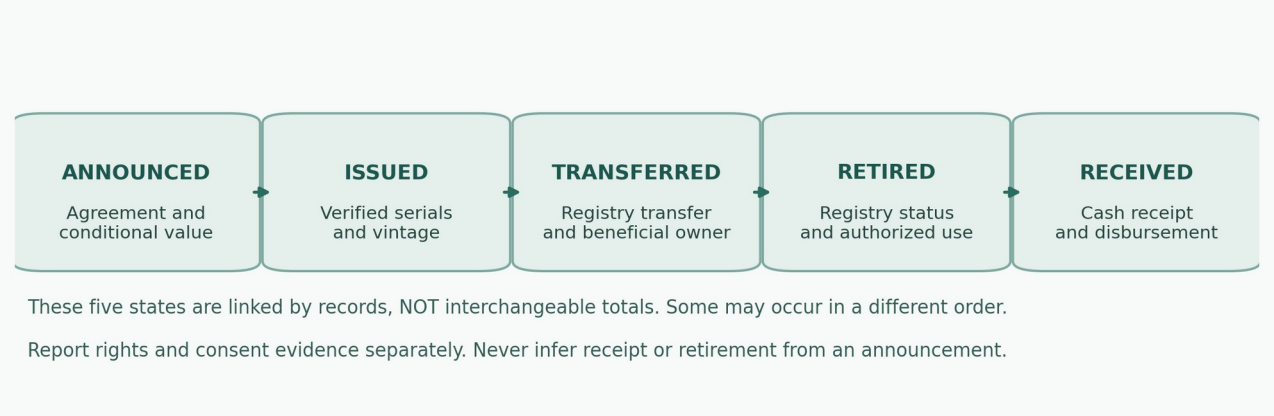


Figure 7. Five finance states that must be reconciled independently before a claim of climate finance delivered is made.

8. Climate finance and carbon-claim integrity

Climate finance is not synonymous with carbon-credit trading. Protected forests receive support through public budgets, philanthropy, bilateral payments, conservation trust funds, debt-related mechanisms, ecotourism and results-based climate programmes. Each instrument has different questions about stewardship, measurable outputs, fiscal accountability and revenue rights. A financial evaluation should connect the instrument's claim to the measurement system rather than assuming every conservation investment purchases an equivalent tonne of atmospheric benefit.

8.1 Five accounting boundaries

Asset boundary. Define the forest, ecosystem and carbon pools included in the stock estimate. A regional inventory is an asset description, not a credit calculation.

Intervention boundary. Identify the legal or practical action under evaluation: new designation, management enforcement, title recognition, restored monitoring, fire control or another intervention. A protected-area label alone does not identify the mechanism.

Counterfactual boundary. Specify the reference outcome absent the intervention, including expected clearing pressure and realistic alternatives. Historical rates alone may not represent future pressure after roads, commodity markets or migration change.

Atmospheric boundary. Translate changes in carbon pools into emissions and removals under explicit decay, recovery, product and gas assumptions. Standing-stock difference and cumulative avoided emissions should not be presented as the same physical event without a carbon-balance model.

Registry boundary. Establish crediting eligibility, vintage, rights, leakage adjustments, buffer treatment, independent verification, issuance, retirement and transfer or authorisation requirements. Reconciliation across national and project accounting is an essential control against duplicate claims.

8.2 Additionality and common failure modes

Additionality tests whether an environmental outcome exceeds what would have happened without the credited intervention. A forest with high historic carbon but limited conversion pressure may qualify for ecosystem funding while presenting a harder case for avoided-deforestation credit additionality. A forest facing genuine imminent conversion might have a clearer counterfactual but also higher leakage or permanence risk. Credit schemes therefore require methodologies rather than applying a uniform percentage to existing stocks.

Over-crediting arises through several routes: optimistic baseline threats, missing carbon pools, overstated biomass density, partial displacement of clearing, double issuance or claiming the same benefit in two jurisdictions. The reverse risk also exists. Satellite systems may miss degradation in standing forests, understated belowground stocks or locally effective management outcomes. Financial diligence should therefore record both direction and magnitude of plausible errors, and separate scientific estimation from contractual entitlement.

8.3 Permanence is a managed obligation

A forest protected today might experience wildfire, drought, illegal clearing or future legal change. Risk buffers, long-term governance, insurance arrangements and periodic verification address different parts of this problem. A carbon stock snapshot does not establish a permanent mitigation effect. Programmes also differ in how they define commitment periods and handle reversals. An external buyer should evaluate the exact applicable standard rather than assuming a single global permanence definition.

8.4 Safeguards and benefit distribution

Forest conservation intersects with property rights, Indigenous tenure, customary access, local incomes and cultural relationships. The legitimacy of project design depends on documented participation and appropriate rights processes. An area might perform well on measured carbon and poorly on social safeguards, or show lower short-term carbon additionality while maintaining high cultural and ecological value. Reporting both dimensions prevents a carbon-only financial score from substituting for broader due diligence.

8.5 Finance-instrument comparison

Instrument	Primary performance question	Suitable evidence	Claim requiring special caution
Public protected-area budget	Were agreed management duties funded and implemented?	Budget, staffing, patrol and ecological monitoring	Avoided emissions without controls
Conservation trust fund	Did disbursements sustain agreed conservation outcomes?	Audited accounts, management plans, indicator series	Assuming every dollar creates credits
Philanthropic conservation grant	Were grant outputs and safeguards achieved?	Independent evaluation and community evidence	Claiming exclusive ownership of public benefits
Jurisdictional results-based finance	Did a jurisdiction meet defined forest performance criteria?	National MRV, standard and verification records	Duplicate project-level claims
Project-level forest credits	Were eligible additional results issued under a named methodology?	Baseline, monitoring, registry and audit trail	Equating total standing stock with credits
Corporate nature investment	What biodiversity, resilience and social outcomes followed?	Mixed ecological and governance indicators	Presenting support as compensation for unrelated emissions

The choice among these instruments is a governance and contractual question as much as a carbon-model question. This paper does not rate them or advise a particular government to adopt one financing route.

8.6 A serialized-claim reconciliation test

For each financing claim, the reporting entity should provide a traceable row containing programme and jurisdiction, reporting period and vintage, credit type and governing standard version, verified issued quantity and serial range, transfer and retirement state, recipient and beneficiary, actual payment date and currency, and the location of authoritative public records. Contract announcements belong in a separate forward-commitment field. Actual local expenditure requires a receipt and beneficiary-level disclosure mechanism with lawful redaction. These fields deliberately exceed a simple total 'carbon revenue' figure: they make it possible to detect duplicated revenue claims, reuse of transferred units and confusion between national emissions accounting and private-market instruments.

For any international claim, identify the applicable accounting pathway and whether a corresponding adjustment is relevant to that specific use, credit and governing agreement. Do not assume every ART-issued credit automatically authorizes every use or that every transaction has identical host-country authorization requirements [36, 39]. Where data are unavailable, mark them *unverified* rather than zero. Missing documentation and a genuine zero are different audit outcomes.

9. Climate, biodiversity and public reporting

The Convention on Biological Diversity's Kunming-Montreal Global Biodiversity Framework includes Target 3, addressing the conservation and management of at least 30% of terrestrial and inland water and marine and coastal areas by 2030 through appropriately governed, ecologically representative, well-connected and equitably managed systems [19]. A climate-carbon metric alone does not establish compliance with the wider target. Public progress reports need attention to effectiveness, representation, connectivity and equitable governance as well as surface area.

The Protected Planet Report 2024 estimated that 17.6% of terrestrial and inland-water areas and 8.4% of marine and coastal areas were documented as protected or conserved at its reporting cut-off. It also reported weaknesses in connectivity, management-effectiveness information and governance data [20]. These are historical 2024 coverage measurements, not a claim about September 2026 live coverage. FAO's different assessment of legally protected forest area, reported in 2025, measures a forest-specific population rather than the land-and-water coverage of Protected Planet [2].

Nationally Determined Contributions under the Paris Agreement, biodiversity strategies under the CBD and national forest inventories serve different formal reporting purposes. The same geographic intervention might appear in several reports, but reporting the outcome under multiple policy frameworks differs from issuing the same transferable emissions reduction more than once. Every institution should preserve programme definitions, geographic boundaries and stock-versus-flow distinctions so users can reconcile published numbers.

9.1 Reporting language with defensible boundaries

Prefer a statement such as: "The reserve contains an estimated X tonnes of aboveground carbon as of year Y, with uncertainty Z under method M." A second, separate statement might read: "Matched comparison areas experienced a higher recorded annual forest-loss rate over years A to B, with a

specified difference and uncertainty." A third might describe additional carbon attributed under the selected counterfactual, conditional on the study's assumptions. Only a registry-specific statement establishes whether a quantity was independently verified, issued or retired as a carbon credit.

Avoid combining reported outcomes into one headline without temporal, pool and geographic reconciliation. Avoid comparing a modelled historical avoided-emissions stock equivalent with a single calendar year's fossil-fuel emissions as though they represent the same flow. Analogies may assist public communication, but the underlying accounting dimensions must remain visible.

10. The Forest Protection Performance Ledger

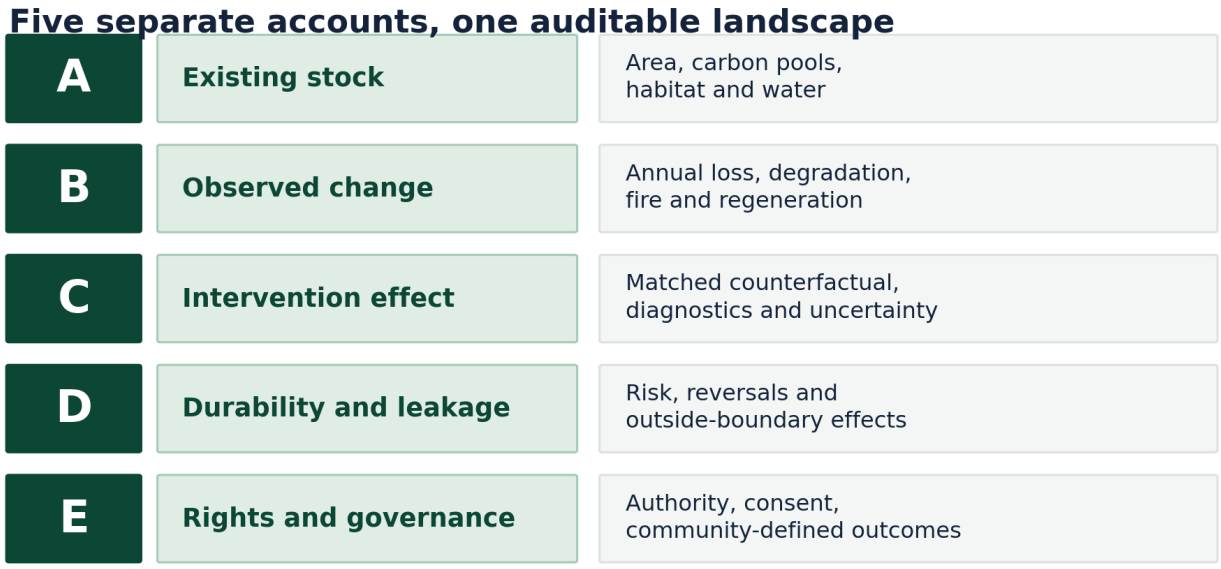


Figure 4. The proposed five-account reporting model separates ecosystem assets, observed change, estimated intervention effects, durability and governance. Original conceptual illustration.

The independent analytical contribution of this paper is the Forest Protection Performance Ledger, a reporting architecture designed to keep scientific and contractual claims in distinct accounts. The ledger is a proposed transparency framework. It has not undergone formal validation as an international standard, is not a new carbon-credit methodology and does not replace national inventory rules. Its usefulness lies in recording five separately auditable dimensions of the same landscape.

Account A: existing ecological asset

Record legal geography and governance, present forest extent, mapped cover classes, aboveground and other separately measured carbon pools, habitat attributes and key water or social services. Tag each datum by observation date, product version, uncertainty and land definition. Report total carbon without suggesting that all existing carbon was retained because of a recent policy intervention.

Account B: observed ecological change

Record annual tree-cover loss, confirmed permanent conversion, mapped degradation, biomass trends, fire disturbance and structural change. Do not use the term “deforestation” for all recorded tree-cover loss. Distinguish natural events, harvest cycles and permanent human conversion according to the source dataset and validation rules. Preserve an event history for boundary changes and management actions.

Account C: estimated intervention effect

Record the causal estimand, eligible sample, matching covariates, before-and-after periods, estimator, balance diagnostics, comparison-pool exclusions, uncertainty interval and sensitivity outcomes. Use an explicit status for sites lacking credible controls. A zero or indeterminate estimate is a research result, not a reason to delete the site from reporting.

Account D: durability and displacement

Record degradation and fire risk, permanence commitments, leakage diagnostics, boundary pressure, observed reversals, long-term finance and management continuity. This account describes risks and monitoring responses, not an arbitrary numerical haircut detached from an accepted methodology.

Account E: governance, rights and wider outcomes

Record management authority, legal designation, tenure and consent processes, community participation, benefit distribution, biodiversity outcomes and grievance mechanisms. Restricted personal or customary knowledge should remain protected. Public transparency does not require exposing sensitive community information.

10.1 A sample reporting page

Ledger line	Illustrative reported field	Mandatory qualifier
Ecological asset	Aboveground carbon: X t C	Measurement year, method and uncertainty
Observed change	Annual forest loss: Y ha	Forest definition and classification accuracy
Intervention effect	Difference: Z t C/ha	Matching quality and confidence interval
Durability	Fire events and leakage test result	Observation horizon and residual risk
Governance	Management and tenure record	Consent, rights and disclosure limitations

A release should append a source manifest, methods protocol, study area map and an issue log for unresolved differences. Financial claims appear in a separate registry-reconciliation note containing the relevant serial numbers and authorisations where public disclosure is permitted. This design enables an academic reader, conservation manager and financial auditor to inspect the same site without assuming that all three users require the same accounting conclusion.

11. Scenarios, uncertainties and decision uses

A useful white paper must make assumptions testable. The following scenarios concern possible future analytical results. They are not forecasts for a particular country or numerical probabilities of future forest loss. Each scenario illustrates how interpretation changes when evidence or management conditions change.

11.1 Scenario A: high stock, low observed pressure

A large, remote forest has high carbon density and low recorded loss in both protected and matched unprotected locations. The protected site has substantial existing ecological value, but a retrospective evaluation finds a small or statistically uncertain additional carbon difference. This result does not establish that designation lacked biodiversity, cultural, watershed or long-term preventive value. It limits only the claim of additional retained aboveground carbon over the observed interval. A crediting assessment would require separate evidence of a credible threat and an applicable baseline.

11.2 Scenario B: high stock, demonstrable pressure outside protection

A protected humid tropical forest and an ecologically matched unprotected control had similar mapped baseline conditions. Over the observation period, the control experienced substantial clearing while the reserve retained most canopy and biomass. Multiple models produce a positive protection-associated difference, the balance diagnostics meet the pre-specified standard, and leakage tests show no detectable near-boundary increase. The estimate offers comparatively strong evidence for an intervention-associated stock difference under its assumptions. Wider commodity-market leakage, unobserved historical tenure and future reversal risk still require separate analysis.

11.3 Scenario C: canopy remains, biomass declines

A forest remains classified as tree cover while repeated lidar and field inventories show a decline in woody carbon density. Selective extraction, drought damage or understory disturbance are plausible mechanisms. An optical clearing metric alone would miss part of the ecological change. The appropriate outcome includes degradation and carbon-pool accounting. Investigators should verify sensor comparability and field evidence before assigning a causal driver.

11.4 Scenario D: apparent reserve success with displaced activity

Annual loss declines inside a protected boundary after new enforcement, but rises near the boundary or in a connected commercial district. A simple reserve-only analysis would overstate net landscape benefit. Local distance-ring tests and trade or infrastructure data help test displacement, while a full market-based assessment might require wider regional modelling. The correct result reports on-site effectiveness and net landscape effectiveness as distinct, uncertain quantities.

11.5 Scenario E: rights-sensitive conservation

An Indigenous-governed landscape records stable forest cover and strong community stewardship but lacks complete data on legal recognition or carbon ownership. Ecological observations support a conservation-performance statement, while missing documentary rights and consent information

prevents a definitive finance-entitlement statement. A monitoring programme should protect sensitive customary information and preserve community agency. A positive carbon result does not resolve a contested land claim.

11.6 Scenario F: climate-driven reversal

A previously intact reserve experiences severe drought and wildfire. A retrospective matching study still reports a historical carbon benefit, but the affected carbon stock and future carbon balance change. New reports need separate event dates, revised observed stocks and documented reversal treatment. The earlier estimate should not be silently deleted, nor should it be presented as an unchanged perpetual climate benefit.

11.7 A transparent uncertainty register

Uncertainty source	How the result might change	Practical test
Historical siting	Overstates or understates protection effect	Alternative matching, designation-date analysis
Biomass algorithm	Shifts carbon stock and site comparisons	Independent biomass product, held-out plots
Carbon conversion	Alters reported carbon mass	Documented factor and field validation
Forest definition	Changes eligible area and loss rate	Multiple canopy thresholds, natural-forest mask
Temporal mismatch	Confounds disturbance with protection	Align observation years, event studies
Spatial autocorrelation	Overstates statistical precision	Spatial blocks and clustered uncertainty
Leakage	Inflates net avoided loss	Multiple boundary zones and regional analysis
Reversal	Reduces durable climate benefit	Event monitoring and time-specific remeasurement
Governance data gaps	Misattributes variation to formal designation	Documentary and participatory verification
Carbon-pool omission	Understates total ecosystem carbon	Root, soil and wetland modules where relevant

This register is part of the analytical result. Each published total should point to the tested sources of uncertainty, state which remain unquantified and avoid combining non-comparable model uncertainties into a false single confidence interval.

12. Institutional implementation options

The technical findings inform several institutional choices without selecting a political programme on behalf of a government or community. A government examining protected-area spending might prioritize a performance audit of existing sites, a landscape-level counterfactual research programme, stronger national inventory integration or expanded participatory governance

documentation. These options answer different questions and carry different data and institutional costs. The relevant choice depends on legal obligations, conservation objectives, capacity, available baseline records and community decisions.

A conservation trust fund might require grantees to report observed management outputs, audited expenditure, ecological indicators and an independent validation cycle. An academic institution might concentrate on pre-registered matched comparisons and publicly released code. A carbon-credit project must additionally satisfy the rules of its named methodology and registry. An Indigenous authority might set local data permissions and define community-selected ecological and social indicators before accepting external monitoring. These approaches should exchange compatible measurements without assuming identical mandates.

12.1 A model reporting cycle

Initial registration: Publish site identifiers, protected-area boundary version, historical designation record, governance category, data-access permissions, outcome definitions, primary estimand and planned sensitivity tests.

Annual reporting: Publish observed tree-cover change, fire and disturbance events, inventory updates where available, management activity, uncertainty flags and significant data or boundary corrections. Ensure a reader can reproduce every published area figure from documented inputs.

Periodic evaluation: At a pre-specified interval, rerun the counterfactual analysis with updated baseline covariates where methodologically justified, publish the matching diagnostics and assess whether new infrastructure or commodity pressure changed the reference landscape. Preserve earlier results as time-stamped historical versions rather than replacing prior estimates without a change log.

Independent assurance: Commission an external review of data lineage, sample design, statistical balance, error budgets, rights-related claims and any financial accounting overlap. Distinguish methodological review from certification under a named credit standard.

Public communication: Supply a short summary and a detailed technical annex. The summary should display stock, observed change, estimated additionality and unresolved risk as different fields. Every numerical headline needs a defined unit, time period and source.

12.2 Core performance indicators

A balanced conservation programme would record both quantified ecological outcomes and the quality of evidence. Suggested indicators include the share of mapped area with validated boundaries, share of forest pixels with usable biomass estimates, annual gross loss by ecosystem, field-plot validation coverage, matched-sample retention, covariate balance, leakage-zone trends, documented fire-related reversals and completeness of governance disclosure. Community-defined indicators should sit beside rather than be overwritten by remote-sensing indicators. Such reporting creates an audit trail without pretending that every ecological and social value reduces to a comparable monetary number.

12.3 Minimum audit release gates for a Guyana pilot

A credible demonstration should choose a bounded pilot rather than claim a national causal effect before estimation. A candidate pilot would select protected and comparison areas with mapped pre-treatment cover, sufficiently dated designation records and reliable access to non-restricted spatial data; register hypotheses and exclusions before calculating impacts; document all national-versus-global forest-definition differences; and request community involvement at protocol stage rather than after findings are drafted. The technical release should require: reproducible source hashes, a covariate-balance table, a common-support map, at least two sensitivity specifications, an independent check of area and carbon unit conversions, and a data-rights log. The governance release should require a documented consent process where applicable, evidence of benefit-sharing procedures, accessible grievance channels and a dispute-sensitive review protocol. The finance release should require a transaction-to-registry reconciliation with no unsupported claim of new creditable tonnes.

These are suggested minimum quality controls, not official UNFCCC or ART requirements and not a representation that all institutions have adopted them.

13. Research gaps and next tests

The scientific literature provides evidence of aggregate carbon benefits in many protected landscapes but leaves several questions unresolved. First, research needs stronger pre-designation biomass baselines where feasible. The GEDI study's earlier-biomass comparability assumption is reasonable for its design but unobserved at the global pixel level. Second, degradation, soil carbon and wetland processes require more consistent integration alongside canopy-clearing metrics. Third, regional and cross-border leakage needs economic as well as spatial analysis. Fourth, studies require more transparent treatment of governance, conservation funding, land tenure and rights without reducing institutions to coarse database labels. Fifth, physical climate risks challenge any assumption that historic carbon retention remains constant through time.

Data improvements help address these problems. Repeated lidar, synthetic-aperture radar, improved biomass modelling, field plots and national inventories provide overlapping measurements with distinct error structures. More comprehensive datasets do not remove the need for pre-registered research questions, defensible counterfactuals and institutional consent. The most useful future output is a transparent, repeated comparison where analysts publish both positive and null results with comparable methods and careful domain definitions.

For Guyana, a scientifically valuable research programme would produce an independently reproducible cross-site baseline, governance-specific comparisons, mangrove-sensitive accounting, and a clear reconciliation between site observations and existing jurisdictional records. Such work would add to the evidence base without implying that this white paper has already completed those measurements.

Closing assessment

The evidence supports a distinction between the large stock of carbon located within protected landscapes and the smaller, model-dependent amount retained because of protection. Duncanson

and colleagues' 2023 GEDI study established an important global benchmark inside its stated latitude and carbon-pool boundaries. Other research confirms substantial regional variation, the relevance of Indigenous and community governance and the need to evaluate forest integrity as well as legal extent. Satellite observations improve measurement, but counterfactual inference, leakage accounting, legal and social safeguards and long-term durability remain separate tasks.

A credible forest-climate report should therefore publish an ecological asset inventory, observed change, an explicitly qualified intervention effect, a durability and displacement assessment, and governance evidence. These accounts are compatible but not interchangeable. The updated Forest Protection Performance Ledger supplies a practical structure for preserving their boundaries and enabling independent scrutiny. The same discipline applies to conservation agencies, Guyana's forest-monitoring system, private finance and global biodiversity reporting.

Technical appendix A. Reproducibility and open-source resources

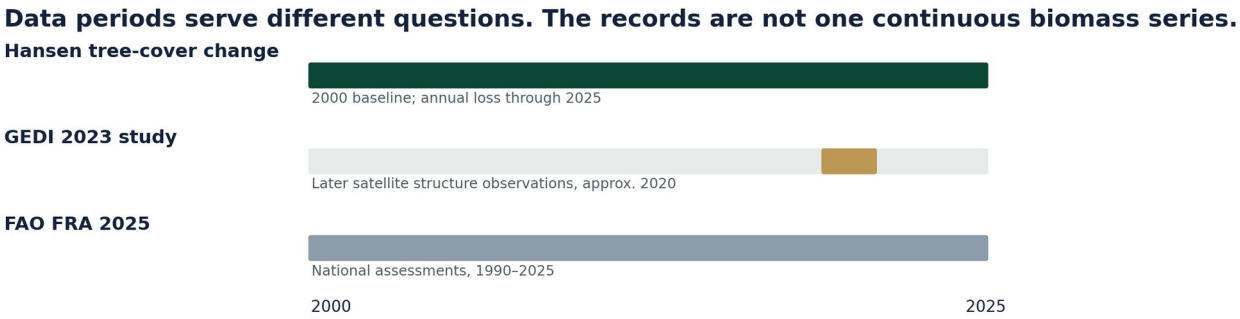


Figure 5. Selected observation windows. Dataset boundaries are schematic and not a claim of continuous GEDI global biomass coverage.

The following technology stack is intended for future implementation. The repositories named here were checked through the public GitHub repository interface during preparation. Their inclusion acknowledges existing software rather than asserting that the global analysis has been rerun for this paper. Use version-pinned releases and review the applicable software licenses before deployment.

Resource	Verified public repository or official portal	Relevance
Google Earth Engine Python/JS API	Earth Engine API	Server-side satellite analysis and global imagery access
geemap	geemap project	Interactive geospatial maps and Earth Engine notebooks
GeoPandas	GeoPandas project	Protected-area geometry processing and spatial joins
Rasterio	Rasterio project	Raster reading, masking, reprojection and quality control
WRI Global Forest Watch Data API	WRI API project	Forest-data access and API infrastructure reference
Hansen Global Forest Change v1.13	Earth Engine catalog	2000 baseline canopy and annual 2001–2025 loss
NASA GEDI L4B v2.1	NASA GEDI DOI	One-kilometre aboveground biomass and standard errors
Protected Planet API v4	Protected Planet API	Current official protected-area metadata and geometry access
FAO FRA 2025	FAO FRA portal	National forest statistics for reconciliation
ESA CCI Biomass	ESA Biomass portal	Alternative biomass observations and time-series checks

The 2025 Hansen release records gross tree-cover loss through 2025 at approximately 30-metre resolution, with the lossyear band encoding losses primarily detected from 2001 onward [14]. NASA GEDI L4B v2.1 supplies one-kilometre aboveground biomass estimates and associated standard errors for its documented observation period rather than a complete annual history back to 2000 [13]. Protected Planet API v4 requires an access token and carries source-specific permissions [21]. A public reproduction package should therefore provide instructions and metadata without redistributing restricted geometry.

A.1 Suggested project structure

```
standing-forests/
  README.md                    Research question and limitations
  CITATION.cff                 Citation metadata
  protocol/analysis-plan.md    Frozen outcomes, controls and exclusions
  config/datasets.yml          Versions, URLs, licenses and dates
  src/acquire/                 Approved official data acquisition
  src/prepare/                 Geometry and raster harmonisation
  src/match/                   Counterfactual matching and diagnostics
  src/estimate/                Carbon, loss and uncertainty calculations
  src/sensitivity/             Alternative models and leakage zones
  tests/                       Spatial and carbon-accounting unit tests
  data/manifests/              Checksums, logs and provenance
  outputs/                     Permitted aggregated tables and figures
  manuscript/                  Human-readable white paper source
```

Keep raw, large rasters outside ordinary Git history. Record asset identifiers, checksums, acquisition date, spatial subsets, terms of use and code revision in each manifest. The repository should contain only licensed or independently authored illustrations. A GitHub release and a permanent archive identifier are suitable after the final manuscript, code and data licenses receive independent review.

A.2 Core pseudo-algorithm

1. Read a frozen protected-area release and eligibility protocol.
2. Resolve overlapping polygons and legal designation dates.
3. Align historical baseline forest cover and pre-treatment covariates.
4. Extract annual loss and biomass observations with source-specific QA.
5. Construct eligible protected pixels and comparable unprotected controls.
6. Match within country, biome, ecoregion and baseline cover strata.
7. Report overlap and covariate balance before effect estimation.
8. Estimate observed stocks, change and matched differences separately.
9. Run alternate forest thresholds, carbon maps and spatial buffers.
10. Test leakage zones and climate-disturbance sensitivity.
11. Validate against field plots, national records and community evidence.
12. Publish outputs, uncertainty, provenance and unresolved limitations.

A.3 Suggested machine-readable dataset registry

```
project: standing-forests-measurable-outcomes
protocol_version: 1.0
primary_outcome: additional_aboveground_carbon_tC_per_ha
secondary_outcomes:
  - annual_gross_tree_cover_loss_ha
  - forest_structure_change
  - leakage_distance_ring_loss_rate
datasets:
  - name: protected_planet
    api: v4
    snapshot_date: REQUIRED_AT_DOWNLOAD
    license_review: REQUIRED
    raw_redistribution: DISABLED_UNTIL_AUTHORISED
  - name: hansen_gfc
    version: 1.13
    coverage: 2000-2025
    source: UMD/hansen/global_forest_change_2025_v1_13
  - name: gedi_l4b
    version: 2.1
    doi: 10.3334/ORNLDAAC/2299
    temporal_scope: PRODUCT_SPECIFIC
  - name: esa_cci_biomass
    version: REQUIRED_AT_DOWNLOAD
    license_review: REQUIRED
```

The entries labelled REQUIRED are intentionally unresolved. No downloaded protected-area snapshot or executed global matching result is represented as an accomplished step in this publication.

Technical appendix B. Carbon calculations and communication controls

B.1 Units and conversion

One gigatonne of carbon is one billion metric tonnes of elemental carbon. A carbon-dioxide mass equivalent for complete oxidation uses the molecular-mass ratio 44/12. Under this purely physical conversion, 9.65 Gt C corresponds to approximately 35.38 Gt CO2 and ±0.88 Gt C corresponds to approximately ±3.23 Gt CO2. The total protected woody stock of 61.43 Gt C corresponds to approximately 225.24 Gt CO2 if all carbon were completely oxidised. These conversions do not indicate actual releases, annual emissions, additional removals or credits. Report the original carbon unit before presenting any converted equivalent.

For a hypothetical 100,000-hectare landscape with modelled aboveground biomass density of 180 tonnes dry matter per hectare, a 0.49 carbon fraction produces an estimated 8.82 million tonnes of aboveground carbon. The factor 0.49 follows the method used by Duncanson and colleagues [1]. Applying it to a different biomass inventory requires review of the underlying species, laboratory and product conventions. Other carbon pools remain excluded. The example is arithmetic, not a new observation at a real site.

B.2 Worked hypothetical counterfactual

Consider 5,000 comparable hectares inside and outside a qualifying reserve. Both sites have modelled baseline woody carbon density of 90 t C/ha. At the end of a twenty-year period, the reserve has 88 t C/ha and its matched unprotected comparison 76 t C/ha. The difference is 12 t C/ha; multiplying by 5,000 hectares gives 60,000 t C of modelled retained stock, or 220,000 t CO2 as a full-oxidation mass equivalent. The reserve itself lost two tonnes of carbon per hectare. A positive *relative* result therefore does not mean that the protected forest absorbed more carbon during the period.

Now suppose 15,000 t C of otherwise avoided regional loss shifted to adjacent land because clearing activity was displaced. A simple illustrative net-landscape difference falls to 45,000 t C before assessing other carbon pools, harvest fate or measurement error. This hypothetical computation is not a recognised leakage or crediting formula. Its purpose is to show why boundary performance and landscape performance require separate statements.

B.3 Prohibited shortcuts in public communication

Avoid presenting global stock as new credits. Avoid describing a cumulative modelled twenty-year difference as one year's observed removals. Avoid treating a study's statistical interval as an all-inclusive systematic error bar. Avoid treating all Hansen tree-cover loss as permanent deforestation. Avoid combining mangrove aboveground carbon with peat or sediment without recording the pool boundary. Avoid assigning economic benefits to Indigenous territories without the responsible authority's rights and consent framework. Avoid borrowing external figures without reviewing attribution and reuse conditions.

Technical appendix C. Audit and peer-review checklist

The checklist below describes the minimum evidence needed before converting this independent secondary review into an original empirical study or a financial-accounting report. Empty fields mean that the underlying work has not been represented as complete.

Audit item	Evidence requested	Release condition
Study protocol	Timestamped outcomes and hypotheses	Frozen before results inspection
Site inventory	Unique boundaries, status, designation year	Overlaps resolved and exclusions documented
Data provenance	Versioned downloads, source links, licenses	Reconstructable from a clean environment
Carbon units	Biomass fraction, pools and conversion	No t C / t CO2 ambiguity
Missing data	Geographic and temporal coverage maps	Missingness quantified
Control quality	Balance plots, overlap and match retention	Predefined diagnostic rules met or failures disclosed
Statistical inference	Spatially appropriate uncertainty	Model assumptions documented
Sensitivity	Threshold, buffer and biomass alternatives	Full results, including null models, released
Leakage	Local rings and wider market discussion	Unresolved residual risk stated
Permanence	Physical and institutional risks	Time period and events disclosed
Community safeguards	Rights, consent and disclosure protocol	Approved with affected authorities
Financial claims	Applicable registry and legal basis	Double-counting checks documented
Independent review	Named scientific and rights review	Comments and responses retained
Publication rights	Figure and dataset licenses	Permissions and attribution cleared

C.1 Suggested independent review questions

A quantitative reviewer should examine whether the comparison sites share sufficient overlap, whether protected-area placement remains a plausible source of bias, whether spatial clustering changes uncertainty and whether conclusions survive the predefined sensitivity suite. A remote-sensing reviewer should test biomass calibration, cloud and canopy classification, mangrove treatment and date alignment. A governance reviewer should inspect conservation authority, rights, participation and claims about local benefits. A finance reviewer should test additionality,

leakage, reversal, jurisdictional nesting and registry reconciliation against the actual applicable methodology.

No one review substitutes for another. A statistically convincing comparison does not settle title to carbon. A registry issuance does not prove broad biodiversity benefits. The objective is to assign every public claim to the evidence and institutional process capable of supporting it.

Technical appendix D. Deep-research update and Guyana accounting crosswalk

D.1 Source hierarchy and quantitative audit

This second edition applies a hierarchy of evidence suitable for a critical reader. Peer-reviewed primary studies support scientific causal and observational claims. UNFCCC technical-assessment reports and national submissions support official national reference-level values, within their own accounting assumptions. NASA and FAO product documentation support definitions and versioning rather than a site-specific protection effect. Registry records support unit-level issuance and disposition. Public institutional announcements support what was announced at the time, not necessarily later transfers, payments, retirement or realised ecological outcomes. Community and civil-society statements document contestable governance positions, and should be attributed in their proper institutional context rather than collapsed into an unqualified conclusion.

Quantitative claim	Evidence origin	Correct denominator or period	What cannot follow
61.43 ± 0.31 Gt C protected-area woody stock	Duncanson et al. [1]	GEDI-study sampled spatial domain	Total global forest carbon or sequestration rate
9.65 ± 0.88 Gt C matched difference	Duncanson et al. [1]	Difference from modelled matched counterfactual	Annual avoided emissions or automatically verified credits
4.14 billion ha global forests	FAO FRA 2025 [2]	Official national-reporting aggregate	Same spatial domain and forest threshold as GEDI study
141.860359 million t CO2e/year	Guyana Dec 2024 submission [30]	Original combined FRL presentation	Current assessed emissions FREL
32.695707 million t CO2e/year	UNFCCC 2025 assessment [29]	Assessed emissions FREL, national-circumstances adjustment	Realised 2025 national emissions
-68.113829 million t CO2e/year	UNFCCC 2025 assessment [29]	Assessed removals FRL, negative sign convention	Additional site-specific removal or a negative credit balance
37.5 million credits and US$750m minimum	Hess / Guyana agreement announcement [34]	Forward commercial agreement as announced in 2022	Verified revenue received or retired unit quantity

One error control is especially important: the initial 141.860359 million and later 32.695707 million plus -68.113829 million are not additive members of a single time series. They reflect a different accounting presentation and components. They also do not share a numerator with the protected-area carbon stock in [1]. Any slide, investment memo or press statement that places them on the same labelled ‘annual climate impact’ axis is methodologically invalid.

D.2 Uncertainty must be decomposed, not buried

At a minimum, report *measurement uncertainty* (GEDI footprint and biomass calibration); *sampling uncertainty* (where GEDI can observe and the location of accessible validation plots); *counterfactual uncertainty* (match quality, historical selection and model specification); *spatial uncertainty* (cluster dependence, edge leakage and region-wide displacement); *temporal uncertainty* (designation dates, reference-period changes, forest regrowth and reversal); and *institutional uncertainty* (boundary and management records, land rights, consent, funding and enforcement). The ±0.88 Gt C published statistical uncertainty is not a universal uncertainty allowance for all these dimensions [1]. A robust study should show sensitivity to plausible alternative forest masks, biomass products, matching algorithms and spillover radii, while reporting null and adverse results.

A matched mean effect for area A and effect density δ can be expressed as $C_{effect} = A \times \delta$, provided A and δ refer to comparable eligible forest pixels, compatible pools and a stated period. For hypothetical mass-equivalent disclosure only, $CO2_{mass_equivalent} = C_{effect} \times (44/12)$. For an avoided-emissions calculation, the required expression instead needs a baseline-minus-observed carbon-change term, a defensible counterfactual time path, leakage, uncertainties, pool and gas coverage, and the applicable registry rules. These are distinct equations with distinct allowable claims; neither can be substituted for the other by a unit conversion [1, 39].

D.3 The public review test

Before a revised estimate is released, its executive summary should disclose: *Who is represented by the sample? What is treatment? What is the no-treatment counterfactual? Which pools and years are counted? Which uncertainties are statistical and which are unquantified? What displaced activity was tested? Which affected communities reviewed the protocol or findings? Does any stated monetary figure refer to an announcement, contract, receipt, disbursement or audited expenditure?* Failure to answer one of these questions does not necessarily disprove a conservation benefit; it limits the level of public claim the available record can substantiate.

Technical appendix E. Reproducible evaluation design and data controls

E.1 Frozen study protocol

Define the treated population by a dated legal-and-management registry of eligible protected areas. Exclude overlapping protection polygons from duplicated area aggregation, while preserving overlapping tenure and governance attributes. Pre-register primary outcomes of forest conversion and aboveground carbon density; secondaries include degradation, fire, forest structure, immediate-ring and distant displacement, and rights and governance process indicators. Specify the local forest definition, sampling threshold, eligible establishment years, treatment timing and time periods before running the estimator. Reserve dedicated strata for mangrove, inland rainforest, savanna woodland, customary tenure and other ecosystems that cannot share a biomass or forest-loss proxy without adjustment.

E.2 Spatial data and preprocessing

Create a geospatial manifest with immutable dataset release name, original URL, licensing condition, acquisition UTC time, content SHA-256, projection, nominal resolution, temporal coverage, missingness mask and interpretation note. Raster processing should keep source-native resolutions until an explicit aggregation step, transform all area calculations to an appropriate equal-area CRS, and account for partially covered boundary pixels. A global tree-cover-loss product should not be relabelled as permanent deforestation without local validation. National MRVS polygons and national driver classifications should remain a separate verification layer when data-sharing terms permit. Protected Planet source polygons must not be redistributed from the public package unless the provider's current terms explicitly allow that use [30, 40].

Dataset	Intended role	Critical qualification
Protected Planet WDPA / conserved areas	Time-stamped treatment polygons	Check terms, boundary precision and designation date [40]
NASA GEDI L4A / L4B	Biomass sample and gridded context	Mission latitude, quality and temporal sampling [41]
Hansen Global Forest Change v1.13	Annual stand-replacement disturbance screen	Canopy threshold and permanent-conversion ambiguity [14]
Guyana GFC MRVS	National definitions and official activity reconciliation	Preserve report-year and method version [10, 30]
FAO FRA 2025	Comparative official national context	Not the counterfactual outcome dataset [2]
ART TREES registry	Serialized credit state	Registry records, vintage and use eligibility [36]

E.3 Identification, diagnostics and stress testing

Construct matched controls within ecological, climate, historical forest-cover and development-access strata. Include pre-treatment travel-time or road-distance proxies, slope, elevation, rainfall,

fire propensity, historical commodity-access pressure and any lawful non-sensitive tenure covariates. Use caliper and overlap diagnostics, report the population discarded for poor common support and freeze decision rules. Cluster uncertainty at the protected-area or meaningful ecological-landscape level and run alternative matching estimators. For sites designated during the remotely observed period, test pre-treatment trend comparability through event-study and difference-in-differences specifications; interpret designs for old reserves as retrospective association where a true pre-treatment baseline does not exist. Exclude immediate adjacency from the *main control pool* only as a contamination control; continue monitoring boundary rings because their exclusion does not prove leakage is absent [1, 31-33].

The minimum results packet should contain descriptive before-after charts, treated and matched-control maps, loss and biomass changes by study year, difference estimates with uncertainty and effective sample size, standardized mean differences before/after matching, pretrend charts where possible, coefficient sensitivity plots, ring-based displacement tests, comparison between two biomass sources where feasible, and a negative-control/placebo specification. If these diagnostics fail, the correct output is a documented inconclusive estimate rather than a substituted favourable number.

E.4 Five-account machine-readable schema

Each unique site-period should carry an immutable site_id and geometry_version; governance_type, designation date and consent-evidence reference; forest_ha, carbon pool and biomass-product version; observed deforestation/degradation and validation status; primary causal estimate, estimator, uncertainty interval, matched-control identifier and balance diagnostics; reversal and leakage flags; rights and grievance process records (with lawful redaction); and separately linked finance records containing contract_id, currency, payment state, crediting standard, vintage, serial range and retirement state. The five accounts should be released as separate compatible tables joined by identifiers, not collapsed into a single climate-impact number.

E.5 Reproduction boundary and red-team checklist

This manuscript's global protected-area figures remain published-source estimates, not new results from its demonstration scripts. The companion bundle contains the figure-building recipes, small source-transcribed Guyana crosswalk, source URLs, a validation script and a template for a future geospatial pipeline. It does not contain restricted raw WDPA polygons, full satellite archives, undisclosed national data or any simulated result represented as empirical. Scientific review should challenge selection assumptions and statistical uncertainty; governance review should evaluate rights, community processes and distributional statements; financial review should trace every serialized unit and reported cash amount. A public correction log should remain open after publication.

References and source register

[1] Duncanson, L., Liang, M., Leitold, V., et al. (2023). The effectiveness of global protected areas for climate change mitigation. *Nature Communications*, 14, 2908. https://doi.org/10.1038/s41467-023-38073-9

[2] Food and Agriculture Organization of the United Nations. (2025). *Global Forest Resources Assessment 2025*. Official release and data platform. https://www.fao.org/forest-resources-assessment/past-assessments/fra-2025/en ; https://fra-data.fao.org/

[3] Geldmann, J., Barnes, M., Coad, L., Craigie, I. D., Hockings, M., & Burgess, N. D. (2013). Effectiveness of terrestrial protected areas in reducing habitat loss and population declines. *Biological Conservation*, 161, 230–238. https://doi.org/10.1016/j.biocon.2013.02.018

[4] Soares-Filho, B., Moutinho, P., Nepstad, D., et al. (2010). Role of Brazilian Amazon protected areas in climate change mitigation. *Proceedings of the National Academy of Sciences*, 107, 10821–10826. https://doi.org/10.1073/pnas.0913048107

[5] Spracklen, B. D., Kalamandeen, M., Galbraith, D., Gloor, E., & Spracklen, D. V. (2015). A global analysis of deforestation in moist tropical forest protected areas. *PLOS ONE*, 10, e0143886. https://doi.org/10.1371/journal.pone.0143886

[6] Geldmann, J., Manica, A., Burgess, N. D., Coad, L., & Balmford, A. (2019). A global-level assessment of the effectiveness of protected areas at resisting anthropogenic pressures. *PNAS*, 116, 23209–23215. https://doi.org/10.1073/pnas.1908221116

[7] Sze, J. S., Carrasco, L. R., Childs, D. Z., & Edwards, D. P. (2022). Reduced deforestation and degradation in Indigenous Lands pan-tropically. *Nature Sustainability*, 5, 123–130. https://doi.org/10.1038/s41893-021-00815-2

[8] Sze, J. S., Childs, D. Z., Carrasco, L. R., & Edwards, D. P. (2022). Indigenous lands in protected areas have high forest integrity across the tropics. *Current Biology*, 32, 4949–4956.e3. https://doi.org/10.1016/j.cub.2022.09.040

[9] Guyana Protected Areas Commission. (accessed September 2026). *National Protected Areas System*, management responsibilities and site profiles. https://www.pac.gov.gy/

[10] Guyana Forestry Commission. (2024). *Guyana MRVS Year 2023 Report*. https://forestry.gov.gy/wp-content/uploads/2024/08/Guyana-MRVS-Year-2023-Report.pdf

[11] Government of Guyana, Department of Public Information. (2024, February 28). Guyana announces CORSIA-eligible ART TREES credits for the 2021 vintage. https://dpi.gov.gy/guyana-announces-worlds-first-credits-eligible-for-use-by-airlines-in-first-phase-of-corsia/

[12] Architecture for REDD+ Transactions. *TREES standard and registry documentation*. https://www.artredd.org/

[13] NASA / Oak Ridge National Laboratory Distributed Active Archive Center. GEDI L4B gridded aboveground biomass density, version 2.1. https://doi.org/10.3334/ORNLDAAC/2299

[14] University of Maryland / Google Earth Engine. Hansen Global Forest Change v1.13, 2000–2025. https://developers.google.com/earth-engine/datasets/catalog/UMD_hansen_global_forest_change_2025_v1_13

[15] Conservation International. (2023). Study: Protected forests are a climate powerhouse. Public article summarising Duncanson et al. https://www.conservation.org/news/study-protected-forests-are-a-climate-powerhouse

[16] Communications Earth & Environment. (2025). Indigenous governance and relationality have effectively avoided forest loss in the Southwest Amazon. https://doi.org/10.1038/s43247-025-02174-8

[17] Guyana Protected Areas Commission. Shell Beach Protected Area, establishment and ecological description. https://www.pac.gov.gy/shell-beach-protected-area/

[18] Guyana Protected Areas Commission. Kaieteur National Park, legal and boundary history. https://www.pac.gov.gy/kaieteur-national-park/

[19] Convention on Biological Diversity. Kunming-Montreal Global Biodiversity Framework, Target 3. https://www.cbd.int/gbf/targets/3

[20] UNEP-WCMC and IUCN. (2024). *Protected Planet Report 2024*. https://digitalreport.protectedplanet.net/

[21] UNEP-WCMC. *Protected Planet API v4 documentation and data-access conditions*. https://api.protectedplanet.net/documentation

[22] European Space Agency. *Climate Change Initiative Biomass data portal*. https://climate.esa.int/en/projects/biomass/data/

[23] Global Forest Watch / World Resources Institute. *Global forest data and methodology resources*. https://www.globalforestwatch.org/ ; https://data-api.globalforestwatch.org/

[24] Food and Agriculture Organization. *Global Forest Resources Assessment 2025 interactive indicators*. https://www.fao.org/interactive/2025/forest-resources-assessment/en/

[25] NASA. *GEDI L4B gridded biomass, version 2.1, official dataset description*. https://data.nasa.gov/dataset/gedi-l4b-gridded-aboveground-biomass-density-version-2-1-5fb8b

[26] United Nations Framework Convention on Climate Change. *The Paris Agreement*. https://unfccc.int/process-and-meetings/the-paris-agreement

[27] Guyana Forestry Commission. *Guyana MRVS assessment, 2022*. https://forestry.gov.gy/guyana-monitoring-reporting-verification-systemmrvs-assessment-report/

[28] World Resources Institute. *Protected Forests, Global Forest Review*. https://gfr.wri.org/forest-designation-indicators/protected-forests

[29] United Nations Framework Convention on Climate Change. (2025, November 22). *Report on the technical assessment of the proposed forest reference level of Guyana submitted in 2025*, FCCC/TAR/2025/GUY. https://unfccc.int/documents/655088 ; https://unfccc.int/sites/default/files/resource/tar2025_GUY_adv.pdf

[30] Government of Guyana. (2024, December 18). *Guyana's Revised REDD+ Reference Level*, submission using reference period 2018-2022. https://redd.unfccc.int/media/guyana_submission_2024-12-18.pdf

[31] Busch, J., & Ferretti-Gallon, K. (2023). What drives and stops deforestation, reforestation, and forest degradation? An updated meta-analysis. *Review of Environmental Economics and Policy*, 17(2), 217-250. https://doi.org/10.1086/725051

[32] Nolte, C., Agrawal, A., Silvius, K. M., & Soares-Filho, B. S. (2013). Governance regime and location influence avoided deforestation success of protected areas in the Brazilian Amazon. *PNAS*, 110(13), 4956-4961. https://doi.org/10.1073/pnas.1214786110

[33] Pfaff, A., Robalino, J., Lima, E., Sandoval, C., & Herrera, L. D. (2014). Governance, location and avoided deforestation from protected areas: Greater restrictions can have lower impact, due to differences in location. *World Development*, 55, 7-20. https://doi.org/10.1016/j.worlddev.2013.01.011

[34] Hess Corporation & Government of Guyana. (2022). Agreement announcement concerning 37.5 million credits and minimum US$750 million ten-year purchase arrangement. https://investors.hess.com/news-releases/news-release-details/hess-corporation-and-government-guyana-announce-redd-carbon

[35] Government of Guyana, Department of Public Information. (2023). First payment from Hess Corporation for Guyana-issued carbon credits. https://dpi.gov.gy/first-payment-from-hess-corporation-for-guyana-issued-carbon-credits/

[36] Architecture for REDD+ Transactions. *ART TREES resources, programme documents and public registry*. https://artredd.org/resources/ ; https://artredd.org/art-registry/

[37] Architecture for REDD+ Transactions. *Complaints and appeals record*, including the 2023 Amerindian Peoples Association matter. https://www.artredd.org/complaints/

[38] Government of Guyana, Department of Public Information. (2023, May 21). Government statement responding to Amerindian Peoples Association's ART TREES complaint. https://dpi.gov.gy/rejection-of-apas-complaint-to-art-trees/

[39] Intergovernmental Panel on Climate Change. (2019). *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Volume 4: Agriculture, Forestry and Other Land Use. https://www.ipcc-nggip.iges.or.jp/public/2019rf/vol4.html

[40] UNEP-WCMC. *Protected Planet: legal terms of use*. https://www.protectedplanet.net/en/legal

[41] NASA. *GEDI mission data products and biomass documentation*. https://gedi.umd.edu/data/products/ ; https://doi.org/10.3334/ORNLDAAC/2299

Reference practice: Digital sources may change after the evidence cut-off. Study [1] provides the quantitative global effect.