ATHLAS VERITY

Green Carbon Calculation Methodology

Satellite-Driven, AI-Powered Carbon Credit Quantification

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Reference Standards: [('gedi-l4a', 'Dubayah, R. et al. (2020). GEDI L4A Footprint Level Aboveground Biomass Density. NASA ORNL DAAC.'), ('sentinel-2', 'European Space Agency. Sentinel-2 MSI Level-2A products (10 m).'), ('sentinel-1', 'European Space Agency. Sentinel-1 C-band SAR Level-1 GRD.'), ('srtm', 'NASA JPL (2003). SRTM 1-arc-second Global. USGS.'), ('ipcc-2006', 'IPCC (2006). 2006 Guidelines - AFOLU Volume 4.'), ('ipcc-2013-wetlands', 'IPCC (2014). 2013 Supplement: Wetlands.'), ('verra-vcs-v43', 'Verra (2024). Verified Carbon Standard v4.3.'), ('iso-14064-2', 'ISO 14064-2:2019. Quantification and reporting of GHG removal.'), ('carbon-fraction', 'IPCC default carbon fraction 0.47 +/- 0.02.')]
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Engine: Green Carbon Verifier Engine · **Project:** Athlas Verity Carbon Verification Engine

1. Purpose & Scope

This document establishes the standardized, fully transparent mechanism for quantifying the emission reductions (tonnes CO2e) of Green Carbon (forest) credits verified by Athlas Verity. It combines satellite remote sensing, open and licensed geospatial datasets, and an artificial-intelligence inference engine into a single auditable pipeline.

Scope — Forest Project Types

- **Forest protection** — Avoided deforestation / degradation of intact forest
- **Forest restoration** — Recovery of degraded forest to a healthy baseline
- **Agroforestry** — Mixed land-use tree-based systems
- **Peat-forest systems** — Forest over organic soils (wetlands supplement)

Aligned Standards

- **Verra Verified Carbon Standard (VCS) v4.3** — Program-level crediting rules and avoidance of double counting
- **ISO 14064-2:2019** — Quantification, monitoring and reporting of GHG reductions
- **IPCC 2006 Guidelines** — Greenhouse Gas Inventories — AFOLU Volume 4
- **IPCC 2013 Wetlands Supplement** — Soil and wetland carbon accounting where applicable
- **CEOS / Cal/Val practices** — Satellite product calibration and validation

2. Satellite Data Acquisition

The engine ingests multi-sensor, multi-temporal satellite data. No single sensor is sufficient: LiDAR provides structural truth, radar penetrates clouds, and optical provides spectral context. The table below defines the operational data stack.

Sensor	Type	Retrieved Variables	Resolution / Revisit	Temporal Coverage	Role in Pipeline
GEDI (NASA, ISS)	LiDAR full-waveform	Canopy height (RH95), vertical structure, AGB training labels	25 m footprints; geolocated pulses	2019-present, periodic revisits over tropics	Structural truth & training labels
SRTM / Copernicus DEM	Radar interferometry	Digital Elevation Model (terrain), slope, aspect	~30 m	Static	Terrain normalization of AGB models
Sentinel-1 (C-band SAR)	Active radar	Backscatter (VH/VV) — proxies for woody structure, works through cloud	10 m, 6-12 day revisit	Continuous	Cloud-independent structure proxy + gap-fill
Sentinel-2 (MSI)	Passive optical	Multispectral bands (B2-B12): NDVI, NDMI, red-edge, SWIR	10 m, 5-day revisit	Continuous	Vegetation indices, species/health, masking
Landsat 8/9 (OLI)	Passive optical	Long time-series spectral indices	30 m, 16-day	1984-present	Historical baseline & change detection
Field plots (aux)	Ground truth	Allometric AGB measurements, species, stem density	Plot-level	Survey campaign	Model validation & bias correction

3. Dataset Inventory

Dataset / Product	Source	Resolution	Frequency
GEDI canoy height (RH95)	NASA GEDI L2A/L4A	25 m pulses	>=1 sample/ha (concentrated)
SRTM 1-arc / C-DEM terrain	USGS / ESA	30 m grid	Static
Sentinel-1 VH/VV backscatter	ESA	10 m	6-12 days
Sentinel-2 MSI reflectance	ESA	10 m (20/60 m bands)	5 days
Landsat 8/9 OLI SR	USGS	30 m	16 days
NDVI / NDMI / red-edge indices	Derived (Sentinel-2)	10 m	5 days
Precipitation / soil moisture	ERA5 / SMAP (aux)	~10-30 km	Daily
Elevation / slope / aspect	SRTM / C-DEM (aux)	~30 m	Static
Training AGB labels	GEDI L4A + field plots	Footprint / plot	Campaign-dependent
Forest mask / strata	JRC / Hansen / local	10-30 m	Annual

Preprocessing note: All products are pre-processed to a common 10 m grid, reprojected to the project CRS, gap-filled with the temporally-nearest valid observation, and cloud/shadow masked using quality bands. Radiometric normalization is applied across acquisitions to ensure a stable multi-temporal signal.

4. AI Engine Architecture

The Green Carbon Verifier Engine is a satellite-to-credit inference pipeline. Each stage is deterministic, logged, and reproducible from raw inputs to final credits.

1 Ingestion & Preprocessing

Reproject, resample to 10 m grid, cloud/shadow masking, BRDF/radiometric normalization, terrain correction.

2 Feature Engineering

Per-pixel stack: spectral bands, NDVI/NDMI/red-edge, SAR VH/VV backscatter, canopy height (GEDI RH95 interpolated), elevation/slope/aspect, temporal aggregates.

3 Gap-filling & Spatial Imputation

Kriging / RF nearest-neighbor fills missing GEDI footprints using optical + SAR covariates.

4 AI Inference Ensemble

RF, XGBoost and Deep CNN (3D cubes) trained on GEDI L4A + field labels, stacked into an ensemble with cross-model variance. Quantile regression forests yield pixel P10/P50/P90.

5 Calibration, Bounds & Conservative Aggregation

Outputs corrected vs held-out plots; polygon AGB capped at IPCC upper bound; agb_conservative = min(agb_p10, capped); carbon = AGB x 0.47; CO_2e = C x 44/12.

6 Baseline / Additionality / Risk

Net reduction vs baseline; leakage, buffer, integrity discount and risk adjustment applied.

7 On-chain Verification

netVerifiedReductionTCO2e written to registry; AURA consensus re-checks bounds and integrity score.

5. Machine-Learning Models

The AI engine is a stacked ensemble. Cross-model disagreement is treated as a source of uncertainty, not ignored.

Model	Input	Validation	Rationale / Output
Random Forest (RF)	Tabular features (spectral indices, terrain, radar).	Spatial cross-validation	Robust, non-linear, feature importance; quantile variant yields P10/P50/P90.
Gradient Boosting (XGBoost)	Same tabular feature matrix.	Spatial CV	High accuracy, handles interaction terms; used as model (b) in stack.
Deep Convolutional Regressor (CNN)	3D feature cubes (bands x lat x lon) around each target.	Spatially-held-out validation	Learns local spatial context (texture, adjacency) that tabular models miss.
Ensemble Stacker	Concatenates RF + XGB + CNN predictions; meta-model (ridge/GBM) fuses them.	Nested spatial CV	Reduces variance; ensemble spread feeds the uncertainty budget.

Training & Calibration Blocks

1. 1. Target definition: AGB (Mg/ha) from GEDI L4A and field allometric plots; matched to predictor pixels.
2. 2. Training strategy: spatially separated train/validation/test folds (no geographic leakage).
3. 3. Uncertainty: quantile regression forests for P10/P50/P90; Monte Carlo dropout optional for CNN.
4. 4. Validation metrics: RMSE, R2, bias, and prediction interval coverage on held-out plots.
5. 5. Calibration: empirical residual correction against independent field plots.
6. 6. Re-training: model re-fit every monitoring cycle (annual) with appended field/satellite data.

Integrity safeguard: spatially separate folds prevent geographic leakage; held-out field plots independently validate every prediction before any credit is issued.

6. Step-by-Step Calculation Procedure

1 Pixel-to-AGB Inference

Ensemble maps each 10 m pixel to AGB with P10/P50/P90. per_pixel_AGB = f(spectral, radar, height, terrain) averaged across the ensemble.

2 Aggregation & Uncertainty

Pixel stats (P10/P50/P90) area-weighted over polygon. uncertainty_percent = ((p90 - p10) / p50) x 100; 15% floor. agb_p50 = polygon mean; agb_p10 = conservative tail.

3 Bounds & Conservative AGB

capped = min(agb_p10, ipcc_max per forest type); agb_conservative_tpha = min(agb_p10, capped) — lower tail capped by scientific upper limit.

4 Biomass -> Carbon -> CO2e

carbon_tc = agb_conservative_tpha x 0.47 x area_ha; co2e_tco2 = carbon_tc x (44/12).

5 Baseline & Additionality

Protection: baseline_agb = agb_current x (1 - deforestation_rate/100)^years. Restoration: explicit baseline_agb_per_ha, degradation decay, IPCC lower bound, or 50% fallback. gross = max(co2_conservative - baseline_co2, 0).

6 Risk / Integrity & Deduction Chain

Score = 0.30 legal + 0.25 data + 0.25 model + 0.20 methodology (IC-A >=85 / 5%, IC-B 70-84 / 10%, IC-C 50-69 / 20%, IC-F <50 / 100%). after_leakage = gross x (1 - leakage/100) [5-20% by area]; after_buffer = x (1 - buffer/100) [20%]; after_integrity; final = x (1 - risk/100), risk = clamp(30 - score/4, 5, 25).

7 On-chain AURA Consensus

AGB re-checked vs IPCC (passed/flags); consensus_confidence = min(100, model_confidence + 10). Result = final_verified_tco2 serialized on-chain.

7. Uncertainty & Conservatism

The engine reinforces structural conservatism with Monte Carlo simulation (N = 1000). Leakage, buffer, baseline and project AGB, carbon fraction and soil carbon are drawn from distributions defined by their mean and standard deviation. The crediting boundary is the lower bound of the 95% confidence interval.

```
uncertainty_margin = max(deterministic_net - lower_crediting_bound, 0)
```

```
net_verified = deterministic_net - uncertainty_margin
```

Each calculation carries an equation trace linking every input to final output, so auditors can reproduce every figure. Issuance never exceeds the CI-95% lower bound — consistent with Verra's conservatism ethos.

8. Numerical Example (End-to-End, Pixel to Credit)

Inputs (500 ha restoration, conservative):

- **Project area:** 500 ha (Restoration, tropical moist forest)
- **Satellite stack:** GEDI RH95 + Sentinel-2 NDVI/NDMI + Sentinel-1 VH/VV + SRTM terrain, 10 m grid
- **Model output (polygon):** agb_p10 = 120 t/ha, agb_p50 = 165 t/ha, agb_p90 = 210 t/ha
- **IPCC bound (tropical moist):** 90-300 t/ha; capped_agb = min(120, 300) = 120 t/ha
- **Baseline:** 60 t/ha (degraded historical cover)
- **Deductions:** leakage 10%, buffer 20%, integrity IC-B (10%), risk_adjustment 12%
- **Carbon fraction:** 0.47; CO2e ratio 44/12

Stage	Calculation	Result
Conservative AGB	`min(agb_p10, cap) = 120 t/ha`	**120 t/ha**
Biomass -> Carbon	`120 x 0.47 x 500`	**28,200 tC**
Carbon -> CO2e	`28,200 x (44/12)`	**103,400 tCO2e**
Baseline CO2e	`60 x 0.47 x 500 x (44/12)`	**51,700 tCO2e**
Gross reduction	`103,400 - 51,700`	**51,700 tCO2e**
After leakage (10%)	`51,700 x 0.90`	**46,530 tCO2e**
After buffer (20%)	`46,530 x 0.80`	**37,224 tCO2e**
After integrity (10%)	`37,224 x 0.90`	**33,502 tCO2e**
Final verified	`33,502 x 0.88`	**29,482 tCO2e**

Conclusion: Of ~51,700 tCO2e potential gross reduction, only ~57% passes to 29,482 tCO2e of validated credits after AI-estimated biomass, conservatism, and the full deduction chain. The entire path from raw pixels to this number is auditable via the equation trace.

9. Verification & On-chain Lifetime

1. The final_verified_tco2 is written to the Athlas Verity registry with a unique serial identifier and full provenance hash (satellite inputs, model versions, and deduction parameters).
2. The AURA consensus step re-checks the AGB against IPCC ranges and re-computes the integrity score before accepting the credit.
3. On retirement, the credit is burned on-chain, producing a verifiable certificate — preventing double counting and enabling independent audit at any time.

10. Regulatory & Compliance Framework

This section defines the compliance pathway through which AV-GC001 credits are rendered eligible, additional, monitored, and independently verifiable under recognised carbon standards. It formalises the audit requirements referenced throughout this methodology.

A. Eligibility & Applicability

Project eligibility. A project is eligible for AV-GC001 crediting only where it demonstrably falls within the applicable scope of this methodology and the governing standards: **Verra Verified Carbon Standard (VCS) v4.3 · ISO 14064-2:2019 · IPCC 2006 Guidelines · IPCC 2013 Wetlands Supplement · CEOS / Cal/Val practices**.

- **Boundary & commencement:** a defined project boundary, a documented start date, and enforceable legal right to the carbon rights being claimed.
- **Land/asset status:** verifiable baseline land-use or asset status at commencement, with no prior registry registration of the same credits (no double counting).
- **Additionally screen:** the activity must not be required by law, regulation, or business-as-usual practice.

B. Additionality Assessment

Additionally is established using a documented, evidence-based procedure consistent with the governing registry (Verra VCS, CDM, ISO 14064-2, or Puro.earth as applicable). The assessment applies a sequential test:

1. **Legal/regulatory test** — confirm no statutory obligation to undertake the activity.
2. **Investment/financial test** — demonstrate the activity is not clearly the most economically attractive course absent carbon revenue (economic analysis against a conservative financial benchmark).
3. **Barrier test** — identify material financial, technological, institutional, or capacity barriers that the carbon revenue overcomes.
4. **Common-practice test** — confirm the activity type is not widespread within the relevant region/asset class.

All assumptions, data, and model outputs supporting the additionality determination are retained in the audit trail for independent review.

C. Monitoring, QA/QC & Sampling Plan

Monitoring plan. A written monitoring plan defines indicators, measurement frequency, instrumentation, and data-retention rules for every crediting interval. All raw inputs (satellite scenes, field records, meter logs, mass-flow data) are time-stamped, georeferenced where applicable, and retained in the auditable registry.

Sampling design. Ground-truth and field sampling follow a stratified random design with documented sample size determined by a target confidence/precision budget, giving statistically valid estimates and defensible uncertainty bounds.

QA/QC. Quality-assurance/quality-control procedures include: duplicate and independent re-measurement checks, instrument calibration traceability, outlier screening, and reconciliation against independent data sources. Any data gap or anomaly is logged and conservatively treated.

D. Third-Party Verification & Audit Trail

Independent verification. Issuance is conditioned on independent desk review and, where required, field or on-site verification by a qualified verifier. The verifier re-checks input provenance, calculation logic, uncertainty treatment, and conservatism settings against this methodology.

Audit trail. Every issued unit carries a unique serial (AV-GC001-[SERIAL]), a provenance hash of all input datasets and model runs, and an immutable on-chain record. On retirement the serial is burned, preventing double counting and enabling independent audit at any time.

Re-verification cycle. Monitoring reports, calculations, and verifier findings are re-assessed at each crediting interval; buffer and risk parameters are re-evaluated against observed disturbance events before further issuance.

E. Permanence, Leakage & Buffer

Permanence & reversal risk. Nature-based removals carry intrinsic reversal risk and are sequestered in a risk-tiered **buffer pool**. Each issued unit contributes to a shared reserve; a non-permanence risk (**NPR**) assessment scores fire, pest/disease, illegal logging, drought, and management failure, and the applicable withholding share is determined conservatively per the governing standard's risk tool. Reversal events are detected via periodic satellite change-detection and are netted against the buffer in the corresponding crediting period.

Leakage. Displacement of land-use or biomass extraction activity outside the project boundary is assessed at each verification using activity-shifting and market-leakage screens. Where leakage is identified it is quantified ex ante to monitoring and deducted from issuable units.

F. SDG Contribution & Safeguards

SDG contribution. Project activities are evaluated against relevant Sustainable Development Goals (SDG 13 Climate Action, SDG 15 Life on Land) with documented co-benefit indicators. **Safeguards.** Environmental and social safeguards include free, prior and informed consent (FPIC) where applicable, stakeholder consultation, protection of high-conservation-value areas, and no net harm to local communities.

11. References

ID	Reference
`gedi-l4a`	Dubayah, R. et al. (2020). GEDI L4A Footprint Level Aboveground Biomass Density. NASA ORNL DAAC.
`sentinel-2`	European Space Agency. Sentinel-2 MSI Level-2A products (10 m).
`sentinel-1`	European Space Agency. Sentinel-1 C-band SAR Level-1 GRD.
`srtm`	NASA JPL (2003). SRTM 1-arc-second Global. USGS.
`ipcc-2006`	IPCC (2006). 2006 Guidelines - AFOLU Volume 4.
`ipcc-2013-wetlands`	IPCC (2014). 2013 Supplement: Wetlands.
`verra-vcs-v43`	Verra (2024). Verified Carbon Standard v4.3.
`iso-14064-2`	ISO 14064-2:2019. Quantification and reporting of GHG removal.
`carbon-fraction`	IPCC default carbon fraction 0.47 +/- 0.02.

12. Key Glossary

Term	Definition
AGB	Above-Ground Biomass - biomass above ground surface (t/ha).
GEDI	Global Ecosystem Dynamics Investigation - NASA LiDAR on ISS.
LiDAR	Light Detection and Ranging - active structural remote sensing.
SAR	Synthetic Aperture Radar - cloud-penetrating active radar.
NDVI / NDMI	Normalized Difference Vegetation / Moisture Indices.
RH95	LiDAR waveform height at 95th percentile - canopy height proxy.
P10/P50/P90	10th/50th/90th percentile of the estimation distribution.
Ensemble	Stacked ML models whose spread quantifies uncertainty.
CO2e	Carbon dioxide equivalent; the unit of carbon credit.
Additionality	Reductions occurring only because of the project.
Leakage	Emissions displaced outside the project boundary.
Buffer pool	Permanent credit reserve against reversibility.
MRV	Measurement, Reporting and Verification.
tCO2e	Tonnes of carbon dioxide equivalent.

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14. Supplementary Notes

14.1 Purpose and Status of This Document

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This document reflects the actual satellite + AI implementation of the Athlas Verity Green Carbon Verifier Engine and is prepared as a reference for compliance, verification, reporting, and carbon standard publication.