ATHLAS VERITY

Blue Carbon Calculation Methodology

Coastal Satellite-Driven, AI-Powered Carbon Credit Quantification

Document: AV-BC001-MTH-01
Version: 2.0 · **Date:** August 5, 2026
Reference Standards: [('vm0033', 'Verra (2023). VM0033 Methodology for Tidal Wetland and Seagrass Restoration, v2.1.'), ('ipcc-2013-wetlands', 'IPCC (2014). 2013 Supplement to the 2006 Guidelines: Wetlands.'), ('ipcc-2006', 'IPCC (2006). 2006 Guidelines - AFOLU Volume 4 (Coastal & Wetlands).'), ('iso-14064-2', 'ISO 14064-2:2019. Quantification, monitoring and reporting of GHG removal.'), ('sentinel-2', 'European Space Agency. Sentinel-2 MSI Level-2A products (10 m).'), ('gem-gmw', 'Global Mangrove Watch (GMW) v3.0 - global mangrove extent 1996-2020.'), ('un-ipcc-rs', 'UN-REDD/IPCC Good Practice Guidance for LULUCF coastal carbon.'), ('carbon-fraction', 'IPCC default carbon fraction 0.45 +/- 0.02 for woody coastal biomass.')]
Status: RELEASED — COMPLIANCE
Engine: Blue 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 and removals (tonnes CO2e) of Blue Carbon (coastal) credits verified by Athlas Verity — including mangroves, seagrass and tidal wetlands. It combines coastal satellite remote sensing, sediment and accretion geochemistry, and an artificial-intelligence inference engine into a single auditable pipeline.

It applies conservative biomass, soil and sequestration accounting aligned with Verra VM0033, the IPCC 2013 Wetlands Supplement, and ISO 14064-2, and is prepared for compliance, verification and carbon-standard publication.

Scope — Forest Project Types

- **Mangrove restoration & protection** — Intertidal forest; AGB + BGB + SOC + accretion pools
- **Tidal wetland / saltmarsh** — Herbaceous coastal wetland; SOC + accretion dominated
- **Seagrass meadow** — Submerged vegetation; SOC + below-ground pools
- **Coastal peat / brackish systems** — Organic-rich coastal soils (wetlands supplement)

Aligned Standards

- **Verra VM0033 v2.1** — Tidal Wetland and Seagrass Restoration methodology
- **IPCC 2013 Wetlands Supplement** — Soil carbon, tidal and coastal wetland accounting
- **IPCC 2006 Guidelines** — AFOLU Volume 4 — coastal and wetland pools
- **ISO 14064-2:2019** — Quantification, monitoring and reporting of GHG removals
- **CEOS / Cal/Val practices** — Satellite product calibration and validation in coastal zones

2. Satellite Data Acquisition

The engine ingests multi-sensor, multi-temporal coastal satellite data. Tidal wetlands require both above-water optical signals and below-canopy bathymetric/radar context; no single sensor is sufficient. The table below defines the operational coastal data stack.

Sensor	Type	Retrieved Variables	Resolution / Revisit	Temporal Coverage	Role in Pipeline
Sentinel-2 (MSI)	Passive optical	Multispectral bands: NDVI, MNDWI, red-edge, SWIR — canopy & water discrimination	10 m, 5-day revisit	Continuous	Ecosystem classification & vegetation indices
Landsat 8/9 (OLI)	Passive optical	Long time-series spectral indices for change & baseline	30 m, 16-day	1984-present	Historical baseline & degradation detection
Sentinel-1 (C-band SAR)	Active radar	VH/VV backscatter — canopy structure, flood/tidal inundation, works through cloud	10 m, 6-12 day revisit	Continuous	Tidal masking & structure proxy
GEDI (NASA, ISS)	LiDAR full-waveform	Canopy height (top-of-canopy) & vertical structure over mangroves	25 m footprints	2019-present	Canopy height & allometric AGB scaling
Bathymetry (Sentinel-3 / SRTM / ICESat-2)	Altimetry / LiDAR	Water depth, intertidal elevation, slope for seagrass & tidal zone	10-300 m	Varies	Submerged habitat & tidal elevation normalization
Sediment cores + UAV/field (aux)	Ground truth	SOC density (g/cm3), accretion rate (mm/yr via 210Pb/137Cs), allometric plots	Core / plot level	Survey campaign	SOC validation, accretion input, bias correction

3. Dataset Inventory

Dataset / Product	Source	Resolution	Frequency
Mangrove extent & strata	Global Mangrove Watch v3.0	10-30 m	Annual, 1996-2020
Sentinel-2 MSI reflectance	ESA	10 m (20/60 m bands)	5 days
Sentinel-1 VH/VV backscatter	ESA	10 m	6-12 days
Landsat 8/9 OLI SR	USGS	30 m	16 days
NDVI / MNDWI / red-edge indices	Derived (Sentinel-2, Landsat)	10-30 m	5-16 days
Canopy height (mangrove)	GEDI L2A + UAV-LiDAR	25 m / plot	Campaign-dependent
Bathymetry / intertidal elevation	Sentinel-3 / SRTM / ICESat-2	10-300 m	Static + revisit
Soil Organic Carbon (SOC) cores	Field cores (210Pb / 137Cs)	Core interval	Campaign-dependent
Accretion rate (mm/yr)	210Pb / 137Cs geochronology	Core interval	Campaign-dependent
Tidal inundation / flooding frequency	Sentinel-1 + tide models	10 m	6-12 days / modeled

Preprocessing note: All optical/SAR products are pre-processed to a common 10 m grid: radiometric and BRDF normalization, cloud/shadow & tidal-inundation masking, geometric co-registration to shoreline, and spatial gap-filling (kriging / RF imputation using SAR + optical covariates). SOC and accretion are handled at core resolution and spatially interpolated within each mapped habitat class.

4. AI Engine Architecture (Coastal Satellite → Carbon → Credit)

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

1 Ingestion & Preprocessing

Reproject and resample optical/SAR to a 10 m grid; radiometric normalization, cloud/shadow and tidal-inundation masking; shoreline co-registration.

2 Feature Engineering

Spectral indices (NDVI, MNDWI, red-edge, SWIR), SAR backscatter (VH/VV), canopy height, intertidal elevation, slope, inundation frequency, temporal aggregates.

3 Coastal Ecosystem Classification

AI classifier (Random Forest / CNN) maps pixels to mangrove / seagrass / saltmarsh / non-vegetated, using spectral + elevation + SAR inputs; strata validated against GMW and field surveys.

4 Biomass Inference

Ensemble regressors (RF, XGBoost, CNN) estimate above-ground biomass (AGB) from canopy height + spectral + SAR features; below-ground biomass (BGB) from root-to-shoot ratios per species/stratum.

5 Soil Carbon & Accretion

SOC from measured cores scaled by classified habitat; accretion rate (210Pb/137Cs) interpolated to project pixels for annual soil carbon sequestration.

6 Flux & Sequestration Model

Combine AGB + BGB + SOC + accretion into an annual carbon flux (tCO2e/yr) per pool, with methane/N2O safeguards where applicable.

7 Uncertainty Quantification

Quantile ensembles emit P10/P50/P90 per pixel; Monte Carlo (N=1000) propagates biomass, SOC, accretion and baseline uncertainty.

8 Calibration & Bias Correction

Residual correction against held-out sediment cores and field allometric plots; ecosystem-level bias removed.

9 Baseline, Additionality & Risk

Reference degradation/scenario (e.g. 30% of project pool) establishes baseline; additionality, leakage, elevated blue-carbon permanence buffer and integrity & risk discounts applied.

10 On-chain Verification

netVerifiedReductionTCO2e serialized with provenance hash and written to the Athlas Verity registry under AURA consensus.

5. Machine-Learning Models

The AI engine is a stacked ensemble. Cross-model disagreement is treated as a source of uncertainty, not ignored. Coastal models are trained on satellite features and validated against sediment cores and field plots.

Model	Input	Validation	Rationale / Output
Random Forest (RF)	Tabular coastal features (spectral indices, SAR VH/VV, elevation, inundation); quantile variant for P10/P50/P90	Spatially-separated folds vs field plots; OOB error	Robust to noise; habitat classification & AGB/SOC regression
XGBoost	Non-linear interactions among spectral, radar & topographic features	Held-out cores & plots; RMSE / R2 / bias	Handles interactions; strong tabular baseline for AGB & SOC
Deep CNN Regressor	3D feature cubes (multi-band, multi-temporal); learns spatial & tidal context	Independent holdout scenes; interval coverage	Learns spatial context; robustness across coastal strata
Ensemble Stacker	Outputs of RF, XGBoost, CNN as meta-features; ridge/GBM meta-model	Ensemble spread tracked as uncertainty budget	Final consensus estimate; spread → uncertainty margin

Training & Calibration Blocks

1. Target definition: AGB (Mg C/ha), SOC density (g/cm3) and accretion (mm/yr) from cores + allometric plots as training labels.
2. Spatially-separated folds by ecosystem stratum & region; strict no-geographic-leakage split.
3. Quantile regression forests + MC dropout for calibrated P10/P50/P90 intervals.
4. Validation metrics: RMSE, R2, bias, and 95% interval coverage vs held-out cores & plots.
5. Empirical residual calibration on independent coastal field campaigns before inference.
6. Annual re-training as new Sentinel/Landsat scenes and accretion data arrive.

> **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 Ecosystem Classification

AI maps each 10 m pixel to mangrove / seagrass / saltmarsh / non-vegetated; compute class area A_class (ha).

2 Above-Ground Biomass (AGB)

agb_conservative = min(agb_p10, cap) per stratum; cap from ecological bounds for each coastal class (Mg C/ha).

3 Below-Ground Biomass (BGB)

bgb = agb * RRS(ratio_stock), root-to-shoot ratio per species/stratum.

4 Soil Organic Carbon (SOC)

soc_stock = sum(SOC_density_core * depth_interval) per stratum, spatially interpolated.

5 Accretion / Annual Soil Sequestration

acc_c = ACCRETION_rate * SOC_density * area; annual soil carbon gain over crediting period.

6 Annual Flux (tCO_2e/yr)

total_C = AGB + BGB + SOC(legacy) + accretion_annual; convert ×44/12 to CO_2e with carbon fraction 0.45.

7 Baseline & Additionality

Baseline = reference degraded pool % (e.g. 30%); additionality verified against counterfactual scenario.

8 Deductions

Apply leakage (%), elevated permanence buffer (%), integrity discount (%), risk adjustment (%) in sequence.

9 Conservatism & Net Credit

net = deterministic_net - uncertainty_margin; capped at CI-95% lower bound; result = netVerifiedReductionTCO2e.

7. Uncertainty & Conservatism

The engine reinforces structural conservatism with Monte Carlo simulation (N = 1000). Biomass, SOC density, accretion rate and baseline degradation 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. Because blue-carbon permanence faces storm, sea-level-rise and land-use risk, an elevated buffer is applied. Issuance never exceeds the CI-95% lower bound — consistent with VM0033 conservatism.

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

Inputs (500 ha restoration, conservative):

- **Project area:** 100 ha (Mangrove restoration, tropical intertidal zone)
- **Satellite stack:** Sentinel-2 MNDWI/NDVI + Sentinel-1 VH/VV + GEDI canopy height + bathymetry, 10 m grid
- **Model output (polygon):** agb_p10 = 96 t C/ha, agb_p50 = 132 t C/ha, agb_p90 = 168 t C/ha; BGB via root-to-shoot 0.49
- **Carbon pools:** AGB+BGB = 120 t C/ha; SOC legacy = 40 t C/ha; SOC accrual = 2.0 t C/ha/yr over 20 yr
- **Baseline:** 30% of project pool (degraded / clearing counterfactual)
- **Deductions:** leakage 10%, permanence buffer 25%, integrity IC-B (10%), risk_adjustment 12%
- **Carbon fraction:** 0.45; CO2e ratio 44/12

Stage	Calculation	Result
Conservative AGB+BGB	`min(agb_p10+bgb, cap) = 120 t C/ha`	**120 t C/ha**
Total Carbon Stock	`(120 + 40 legacy) = 160 t C/ha × 100 ha`	**16,000 t C**
Accretion Soil C (20 yr)	`2.0 t C/ha/yr × 100 ha × 20 yr`	**4,000 t C**
Gross Carbon (pools+accretion)	`16,000 + 4,000 = 20,000 t C`	**20,000 t C**
Gross CO2e	`20,000 × 44/12 = 73,333 t CO2e`	**73,333 t CO2e**
Baseline (30% degraded)	`73,333 × 0.30`	**22,000 t CO2e**
Net after leakage (10%)	`(73,333 - 22,000) × 0.90`	**46,200 t CO2e**
After buffer (25%)	`46,200 × 0.75`	**34,650 t CO2e**
After integrity (10%) & risk (12%)	`34,650 × 0.90 × 0.88`	**27,443 t CO2e**

Conclusion: Of ~73,333 tCO2e gross pools and accretion, only ~37% passes to 27,443 tCO2e of validated credits after baseline degradation, leakage, the elevated blue-carbon permanence buffer, integrity and risk conservatism.

9. Verification & On-chain Lifetime

1. The final_verified_tco2 is written to the Athlas Verity registry with a serial number per vintage (AV-BC001-{serial}) and a provenance hash of all input datasets and model runs.
2. AURA consensus re-checks the arithmetic and conservatism bounds; every credit is traceable to its source polygon, satellite scene set and sediment-core evidence.
3. On retirement, the credit certificate is minted and the serial is burned on-chain, preventing double claiming of the same coastal carbon removal.

10. Regulatory & Compliance Framework

This section defines the compliance pathway through which AV-BC001 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-BC001 crediting only where it demonstrably falls within the applicable scope of this methodology and the governing standards: **Verra VM0033 v2.1 · IPCC 2013 Wetlands Supplement · IPCC 2006 Guidelines · ISO 14064-2:2019 · 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-BC001-[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. Blue-carbon systems (mangroves, seagrass, tidal wetlands) store carbon in biomass and sediment but face reversal via coastal development, aquaculture conversion, hydrology change, and storm surge. Units contribute to a **buffer pool** sized by a non-permanence risk (**NPR**) assessment covering these disturbance vectors, with satellite + field change-detection triggering buffer drawdown where a reversal is observed.

Leakage. Displacement of conversion or harvesting activity to neighbouring coastal areas is screened via land-use change analysis and netted from issuance where detected.

F. SDG Contribution & Safeguards

SDG contribution. Activities are evaluated against SDG 13 (Climate Action), SDG 14 (Life Below Water) and SDG 6 (Clean Water) with documented co-benefits for coastal protection and biodiversity. **Safeguards.** FPIC and engagement of coastal communities, protection of high-conservation-value habitats, and no net harm to fisheries or livelihoods are enforced.

11. References

ID	Reference
`vm0033`	Verra (2023). VM0033 Methodology for Tidal Wetland and Seagrass Restoration, v2.1.
`ipcc-2013-wetlands`	IPCC (2014). 2013 Supplement to the 2006 Guidelines: Wetlands.
`ipcc-2006`	IPCC (2006). 2006 Guidelines - AFOLU Volume 4 (Coastal & Wetlands).
`iso-14064-2`	ISO 14064-2:2019. Quantification, monitoring and reporting of GHG removal.
`sentinel-2`	European Space Agency. Sentinel-2 MSI Level-2A products (10 m).
`gem-gmw`	Global Mangrove Watch (GMW) v3.0 - global mangrove extent 1996-2020.
`un-ipcc-rs`	UN-REDD/IPCC Good Practice Guidance for LULUCF coastal carbon.
`carbon-fraction`	IPCC default carbon fraction 0.45 +/- 0.02 for woody coastal biomass.

12. Key Glossary

Term	Definition
Mangrove	Intertidal salt-tolerant forest storing carbon in biomass and soil.
AGB / BGB	Above-Ground / Below-Ground Biomass - living plant carbon pools.
SOC	Soil Organic Carbon - carbon stored in wetland sediment.
Accretion	Vertical sediment + carbon accumulation rate (mm/yr; t C/ha/yr).
210Pb / 137Cs	Radionuclides used to date sediment cores and derive accretion.
MNDWI	Modified Normalized Difference Water Index - water/tidal discrimination.
VM0033	Verra methodology for tidal wetland and seagrass restoration.
P10 / P50 / P90	10th/50th/90th percentile of the estimation distribution.
Buffer pool	Elevated reserve covering permanence risk (storm, SLR, land-use).
Additionality	Reductions/removals occurring only because of the project.
tCO2e	Tonnes of carbon dioxide equivalent - unit of carbon credit.
MRV	Measurement, Reporting and Verification.
Intertidal zone	Area exposed at low tide, inundated at high tide - key habitat.
AURA consensus	Athlas Verity on-chain verification & provenance protocol.

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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 Blue Carbon Verifier Engine and is prepared as a reference for compliance, verification, reporting, and carbon standard publication.