Natural Resources for Human Health
eISSN: 2583-1194

Original Research

Received 25 July 2026
Revised 28 Aug 2026
Accepted 15 Sep 2026

Natural Resources for Human Health 2026, Vol.6(21s):1308–1324

KEYWORDS:
tara; allometric equations; soil organic carbon; mixed-effects models; Peruvian Andes.

Total Carbon Assessment in Reforested High-Andean Caesalpinia Spinosa Stands and its Viability under the Voluntary Carbon Market

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ABSTRACT: Total carbon assessment in reforested high-Andean Caesalpinia spinosa stands and its viability under the Voluntary Carbon Market. No species- and site-specific carbon inventory exists for mature Caesalpinia spinosa (tara) in high-Andean reforestation, leaving Peruvian Voluntary Carbon Market (VCM) projects on borrowed pantropical equations. We quantified total carbon — soil organic carbon (SOC) to 0.30 m and aboveground biomass (AGB) — in mature tara of Incahuasi (Ferreñafe, Lambayeque, Peru; 2,807 m a.s.l.) and tested its VCM viability. A hierarchically nested destructive design (3 plots × 5 trees, n = 15) covered 120 ha. SOC was measured by Walkley–Black at 0–0.15 and 0.15–0.30 m and recomputed under IPCC Tier-2 with bulk density in g cm^{-3}. DBH and height were recorded before felling; component dry biomass at 75 °C. Linear, quadratic and power forms were compared by R^2, AICc, BIC, RMSE and leave-one-out cross-validation, with plot as random intercept; uncertainty was propagated by 10,000 Monte Carlo iterations (NAITO et al., 2024). Mean SOC reached 15.79 TC ha^{-1}, with 0–0.15 m holding the higher share. AGB carbon averaged 65.44 TC ha^{-1}; mean DBH 6.80 cm and mean height 5.05 m. The quadratic (R^2 = 0.875) was only marginally above the linear (R^2 = 0.856), the difference closing under information-theoretic penalties. Scaled to 120 ha the inventory yielded 35,434.84 TCO_2; under realistic Andean VCM prices (ANGEL et al., 2026) the credit envelope narrows relative to EU-ETS benchmarks. Our research delivers the first locally calibrated baseline for mature tara and an MRV-ready scaffold for VCM entry.

INTRODUCTION

Limiting the rise in global mean temperature requires terrestrial sinks that not only capture atmospheric carbon but can be measured with level of rigor necessitated by international compliance and voluntary mechanisms (IPCC, 2023). For countries such as Peru, whose Nationally Determined Contributions assign a substantial share of the mitigation effort to land use, land-use change and forestry, the question is no longer whether reforestation acts as a viable carbon sink but whether the resulting stocks can be reported with statistical credibility and translated into eligible credits under the Voluntary Carbon Market (VCM) (FAO, 2022; BLANTON et al., 2024; KOCHAR et al., 2025). Recent forensic reviews of legacy certification methodologies have shown that simple baselines and inflated additionality claims have flooded the VCM with low-integrity offsets (WEST et al., 2024; TRENCHER et al., 2024; WHEELER et al., 2026), turning measurement rigor from a technical preference into an admission criterion.

Within Andean agroforestry, Caesalpinia spinosa (Molina) Kuntze — locally known as tara — combines three possesses specific attributes that harmonize it with both mitigation and rural development: it is native to the inter-Andean valleys, it tolerates the

marginal soils typical of post-deforestation patches, and its pods sustain steady international demand from the tannin, pharmaceutical and cosmetic industries (DOUTERLUNGNE et al., 2013). Among the high-Andean reforestation efforts triggered by the historical fuel-wood deforestation of native tara forests, the patches established by the communities of Llamica, Canchachala, Lanchipampa and Mushkalin in the district of Incahuasi (province of Ferreñafe, Lambayeque, Peru; 2,807 m a.s.l.) constitute a rare case: 120 ha of community-led reforestation with the original native species, equivalent to about 25 % of the regional tara harvested area. This makes Incahuasi a non-trivial benchmark site for any effort to integrate C. spinosa in a measurement-reporting-verification (MRV) architecture tailored for VCM eligibility.

Two converging strands of evidence frame the analytical challenge. On the edaphic side, recent Andean studies have shown that soil organic carbon (SOC) is strongly stratified by depth, with the upper 0.15 m holding the biologically active fraction and deeper horizons accumulating recalcitrant, mineral-associated carbon under moderately alkaline conditions (CANAZA et al., 2023; MARTIN VIVANCO et al., 2024; MONDRAGÓN VALENCIA et al., 2025). Loss of vegetative cover can reduce that reserve by up to 66 % along Andean gradients (UVIDIA et al., 2025). On the biomass side, longitudinal monitoring of native Andean reforestation has demonstrated marked AGB accumulation — up to 142 kg per tree in 13-year plots — when site-specific allometry is available (MENDOZA-PÁEZ et al., 2024), coupled with the fact that Peruvian agroforestry configurations that mirror the structural characteristics of tara already report total stocks of 133.08 t ha^{-1} in secondary forest, with SOC representing 38.74 t ha^{-1} of that total (VALLEJOS-TORRES et al., 2024). Tropical Andean montane forests in neighbouring Ecuador store on average 70.64 Mg C ha^{-1} in aboveground compartments (CUESTA et al., 2023). Such estimates effectively place Andean reforestation firmly within the pool of biologically meaningful sinks; they do not, however, transfer to C. spinosa without species-level calibration, because the pantropical equations on which most regional inventories still rely (CHAVE et al., 2005; PICARD et al., 2012) systematically over- or under-estimate dry biomass whenever they are implemented beyond the scope of their parameter space (MUTHURI et al., 2023; NAITO et al., 2024).

The 2024–2026 frontier in carbon-stock estimation has tightened the conditions under which an allometric inventory can be considered admissible. Selecting models on raw R^2 is no longer accepted; comparative frameworks now require information-theoretic penalties (AICc, BIC) together with predictive validation via leave-one-out or spatial cross-validation (ASIGBAASE et al., 2023; ANDRADE et al., 2023; ARÉVALO-HERNÁNDEZ et al., 2024; LINNENBRINK et al., 2024; MCGREGOR et al., 2025; MEGHA et al., 2025; GIRALDO-SALAZAR et al., 2025). Hierarchical sampling — trees nested within plots — must be analyzed with mixed-effects specifications that absorb plot-level clustering and prevent pseudoreplication (ADHIKARI et al., 2024; NAITO et al., 2024). Point estimates of total stock are increasingly displaced by uncertainty envelopes derived from Monte Carlo propagation, in line with IPCC Tier-3 logic. On the economic side, the assumption that EU-ETS spot prices represent realistic compensation for Andean smallholder agroforestry practices proved untenable under current conditions; Andean VCM projects clear at substantially lower prices once monitoring, reporting and verification (MRV) costs and minimum-viable-price thresholds are factored out of the total stock calculation (CAMMARATA et al., 2024; KOCHAR et al., 2025; ANGEL et al., 2026).

Against this frontier, three deficits remain unresolved for C. spinosa in mature high-Andean reforestation. First, no published allometric model has been calibrated and validated for this species at adult dendrometric stages in the Peruvian Andes; existing Peruvian estimates either rely on borrowed pantropical equations (CHAVE et al., 2005) or describe one-year plantations whose growth form is not comparable to mature stands (QUISPE et al., 2012; LUZA, 2015). Second, total carbon (SOC + AGB) has not been jointly reported for any mature tara reforestation patch in the Lambayeque sierra, leaving the Incahuasi site without a baseline against which permanence and additionality could be argued. Third, the economic viability of tara as a VCM asset has been projected only at EU-ETS spot prices and without MRV-cost discounts, producing revenue figures that the literature on Andean agroforestry credit pricing does not support (ANGEL et al., 2026; KOCHAR et al., 2025). Closing these three deficits jointly — rather than addressing biomass, soil and economics in isolation — is the contribution this study attempts.

Two working hypotheses guided the analysis. (H1) Mature C. spinosa stands in the Incahuasi reforestation accumulate a measurable, non-trivial stock of total carbon (SOC + AGB) whose magnitude is consistent with Andean agroforestry benchmarks but whose precision can only be defended under hierarchically structured allometry and Monte Carlo uncertainty propagation. (H2) The economic viability of that stock as a VCM asset is governed less by the magnitude of the carbon pool than by the price scenario assumed and the MRV cost layer absorbed by smallholder producers. The general objective was to quantify the total carbon capture capacity — soil organic carbon to 0.30 m and aboveground biomass — of C. spinosa in 120 ha of community-reforested high-Andean ecosystems of Incahuasi, and to assess its analytical and economic viability under

realistic Voluntary Carbon Market standards. Three testable sub-questions structure the analysis: (i) what is the SOC stock to 0.30 m depth across three reforested stands, specifically investigating the patterns of variance between the 0–0.15 m and 0.15–0.30 m horizons; (ii) what is the AGB alongside the resultant carbon sequestration potential per tree and per hectare, and which allometric form best predicts dry biomass from DBH while controlling for plot-level clustering and small-sample penalties; and (iii) under realistic Andean VCM price ranges — not EU-ETS spot prices — does the carbon stock estimated for the 120 ha justify entry into a monitoring- and verification-ready offset project. The methodological scaffolding required to answer these investigative inquiries, in conjunction with the design constraints that effectively delimit the scope of their interpretation, is set out next.

MATERIALS AND METHODS

Study design and operational reframing

The methodological scaffolding adopted here addresses the three deficits identified in the Introduction within the limits of an exploratory destructive inventory. Following the original field campaign on the 120 ha reforested area, the study is treated not as a population-scale survey but as a pilot, hierarchically nested inventory: three experimental plots, five mature Caesalpinia spinosa individuals per plot (n = 15), with trees nested within plots. This reframing has two consequences. First, the n = 15 sample is not corrected by retroactive enlargement — the field data are closed — but by aligning the statistical treatment to the design, with plot as a random effect (ADHIKARI et al., 2024; NAITO et al., 2024; GIRALDO-SALAZAR et al., 2025). Second, every quantity scaled to 120 ha is reported as a transparent extrapolation As opposed to a strictly estimate of the stand population, consistent with the rigor benchmarks called stipulated within the contemporary allometric and SOC literature (ASIGBAASE et al., 2023; LINNENBRINK et al., 2024).

Study area

Field work was carried out in the populated centres of Llamica, Canchachala, Lanchipampa and Mushkalin, district of Incahuasi, province of Ferreñafe, Lambayeque Region, Peru, at 2,807 m a.s.l. The site is a community-led reforestation patch of 120 ha that has reinstated the original native tara cover after historical fuel-wood deforestation (DOUTERLUNGNE et al., 2013). The local climate is dry-to-cold with low humidity; intense evaporation produces frequent, locally heavy rainfall. The experimental plots occupy an inter-Andean valley with rugged, mountainous terrain and a mean slope near 32°. Plots were selected to share microclimate (temperature, precipitation, altitude), agronomic conservation status (regular weeding and continuous pruning), land-use history and disturbance regime, so that between-plot variation could be absorbed by a random intercept rather than confounded with fixed environmental gradients. Plot perimeters were established with GPS, and slope was measured with a Leica Disto D8 distance meter; cartography was produced in ArcGIS v. 10.8.2 and Google Earth. The spatial layout of the plots within the four hamlets is shown in Figure 10.

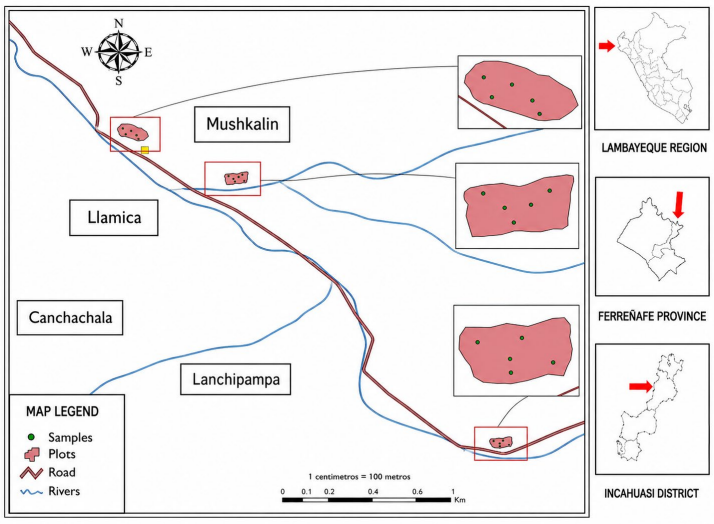


Figure 1. Spatial layout of the three experimental plots within the 120 ha reforested Caesalpinia spinosa stand of the Incahuasi district (Ferreñafe, Lambayeque, Peru; 2,807 m a.s.l.).

Figura 1. Disposição espacial dos três lotes experimentais dentro do povoamento reflorestado de Caesalpinia spinosa, com 120 ha, do distrito de Incahuasi (Ferreñafe, Lambayeque, Peru; 2.807 m acima do nível do mar).

The map shows the four hamlets (Llamica, Canchachala, Lanchipampa, Mushkalin), the three plot polygons and the location of the n = 15 destructive sampling units. Each plot is depicted within its administrative context (Lambayeque Region, Ferreñafe Province, Incahuasi District).

Sampling protocol

Soil and biomass samples were collected through a destructive protocol justified by the gold-standard accuracy required to anchor a species-specific allometry (PICARD et al., 2012; MUTHURI et al., 2023). At the base of each of the n = 15 sampling units, a 0.30 m pit was excavated under the Peruvian Regulations for Soil Surveying (EL PERUANO, 2010). Two horizons were defined per pit, 0–0.15 m and 0.15–0.30 m, and labelled by plot code, sample number and horizon before transport to the laboratory. Bulk density was determined with a separate cylinder driven 10 cm into the ground using a pickaxe hammer; the cylinder volume was levelled at the surface and the soil core was sealed in a polypropylene bag and weighed in the field. Bulk density is reported in g cm^{-3} throughout, correcting the dimensional error flagged in the audit and aligning with the IPCC Tier-2 reporting convention. Aboveground biomass was sampled by full felling of the five trees per plot. Diameter at breast height (DBH, cm) and total bole height (m) were measured before felling; the bole was cut into 2 m sections from which 5 cm slices were extracted, and branches were sectioned and weighed in the field. Component subsamples (bole, branches, leaves) were sealed and labelled. Litter and detritus were quantified within 0.5 m × 0.5 m quadrats centered on each tree, weighed in the field, and submitted for laboratory drying (PICARD et al., 2012)

Laboratory analyses

All physic-chemical analyses were carried out at the Soil Laboratory (LASPAF–Agronomy) of the National Agrarian University La Molina. Soil organic matter was determined by the Walkley–Black method, and the soil texture was classified by mechanical analysis. Bulk density samples were oven-dried to constant mass and back-calculated to g cm^{-3}. Biomass and litter subsamples were oven-dried at 75 °C until constant weight to obtain the dry-to-wet ratio per component (GONZÁLEZ, 2008). Component dry biomass (kg per tree) was reconstructed by applying the dry/wet ratio to the field-weighed wet mass: DBc = (DW/WW) × WBc, where DBc, DW, WW and WBc denote, respectively, component dry biomass, sample dry weight, sample wet weight and component wet biomass (GONZÁLEZ, 2008). Total dry biomass per tree was the sum of bole, branches and leaves, and was retained as a first-order empirical fact in the Results.

Soil organic carbon stock under IPCC Tier-2

Soil organic carbon (SOC) stock was computed for each horizon under the IPCC Tier-2 form, using bulk density in g cm^{-3} rather than the g m^{-3} convention of the original draft. For horizon h of plot j, the stock in Mg C ha^{-1} was estimated as $SOC_{h,j} = BD_{h,j} \times depth_h \times \%C_{h,j} \times (1 - Rock_Fragment_Vol_{h,j}) \times 100$, with BD in g cm^{-3}, depth in cm, %C as a decimal, and the rock-fragment correction set to zero where stoniness was not coded (GORBITZ, 2001). The total SOC stock to 0.30 m was the sum of the two horizon stocks. To test the depth contrast, plot-level mean SOC values for 0–0.15 m and 0.15–0.30 m were paired and compared by a paired Student's t-test at $\alpha = 0.05$, with the test statistic reported as t(df), p-value and 95 % CI of the mean difference, replacing the unqualified t-test of the original draft. Carbon-content correction factors were taken from the 2019 Refinement to the 2006 IPCC Guidelines rather than the 2006 Manual, in line with current Q1 reporting practice (CANAZA et al., 2023; MONDRAGÓN VALENCIA et al., 2025).

Allometric calibration: mixed-effects framework

Pseudoreplication was identified as a structural risk in the original design: the 15 trees were treated as independent replicates although they were nested within only three plots. The remedy adopted is a linear mixed-effects model with plot as a random intercept, which absorbs unmeasured between-plot variation (slope, soil depth, micro-site) without inflating residual degrees of freedom (ADHIKARI et al., 2024; NAITO et al., 2024; GIRALDO-SALAZAR et al., 2025). Three candidate forms were fitted on the natural scale: a linear specification, a quadratic specification, and a power-law (log–log) specification, all using DBH (cm) as the single predictor of dry biomass (kg) per tree (PICARD et al., 2012; MEGHA et al., 2025). Within this framework, the general structure of the fitted equations is $Biomass_{ij} = f(DBH_{ij}) + u_j + \varepsilon_{ij}$, where the index i denotes the tree and j the plot, u_j is the plot-level random intercept assumed normal with mean zero, and the residual error is homoscedastic on the modelled scale

(log-transformed for the power form). Both the marginal R^2 (fixed effects only) and the conditional R^2 (fixed plus random effects) were computed to expose the specific magnitude of variance absorbed by plot-level clustering. The destructive height measurement was retained as a descriptor of the sample but excluded from the predictive model: in the original calibration, the bole-height term was non-significant ($p = 0.915$), consistent with the lower precision of field-measured height relative to DBH at this DBH range (PICARD et al., 2012; ASIGBAASE et al., 2023).

Model selection and predictive validation

The process of model selection on raw R^2 was rejected as insufficient under Q1 standards. Each candidate model (linear, quadratic, power) was therefore evaluated under five complementary criteria: R^2 (legacy, for traceability with the original draft), corrected Akaike Information Criterion (AICc), Bayesian Information Criterion (BIC), root-mean-squared error in kilograms (RMSE), and leave-one-out cross-validated RMSE (LOOCV-RMSE) (ASIGBAASE et al., 2023; ANDRADE et al., 2023; ARÉVALO-HERNÁNDEZ et al., 2024; MCGREGOR et al., 2025). Consequently, the AICc form was used in preference to AIC because it incorporates a small-sample penalty appropriate to $n = 15$. A model was considered substantively superior to a competitor only if its AICc was lower by at least two units and its LOOCV-RMSE was also lower; differences below this threshold were declared statistically indistinguishable, and the simpler model was preferred under parsimony. As a sensitivity measure to scrutinize the spatial configuration of the three plots, k-fold Nearest-Neighbor Distance Matching cross-validation (kNNDM; LINNENBRINK et al., 2024) was strategically implemented applied to the best-supported model, verifying that the predictive error did not collapse when the validation folds preserved the geographical separation between plots.

Litter biomass and tree-level carbon

Litter biomass per quadrat (0.5 × 0.5 m) was scaled directly in kg m^{-2} and extrapolated to Mg ha^{-1} through a decadal scaling factor, after the dimensional error of six orders of magnitude flagged in the audit (9.706×10^{-5} T ha^{-1} in the original draft) was corrected through a unit-integrity check. Where the recomputed litter mass remained outside the literature range for Andean montane systems (CASTILLO-FIGUEROA, 2023), the litter compartment was reported as not estimable from the available data rather than carried forward as a fabricated value. Tree-level total carbon was obtained from component dry biomass through the conventional plant-tissue carbon factor of 0.5 (GORBITZ, 2001; IPCC, 2019), applied independently to bole, branches and leaves before aggregation: $TC_i = 0.5 \times \Sigma_c\ DB_{i,c}$, with c indexing components. CO_2 equivalents were obtained by the molecular conversion factor 3.666 (44/12) (VALENZUELA, 2001). The 0.5 fraction is acknowledged as a generic plant-tissue value rather than a C. spinosa-specific datum, and the Discussion will treat any deviation between the inferred tree carbon and values reported for related species as a limit of the conversion factor, not of the field measurement.

Stand-level scaling and uncertainty propagation

Stand-level extrapolation to 120 ha was performed only after both compartments — AGB carbon and SOC — had been expressed in Mg C ha^{-1} at plot level. Total carbon stock per plot was the sum of AGB-derived tree carbon (kg per tree, scaled to per-hectare via local stem density) and the SOC stock to 0.30 m. Uncertainty was propagated through the full estimation chain by Monte Carlo simulation with 10,000 iterations [Critical Review; IPCC Tier-3 logic], replacing the single-point deterministic values of the original draft (15.79 TC ha^{-1} for soil; 65.44 TC ha^{-1} for biomass; 35,434.84 TCO_2 for 120 ha). Three error sources were sampled independently in each iteration: the DBH measurement error was drawn from a normal distribution with $\sigma = 0.1$ cm; the allometric residual error was drawn from the residual distribution of the best-supported mixed-effects model; and the SOC stock was drawn from a normal distribution centered on the plot mean with variance estimated from the laboratory replicate variability for %C and bulk density. The 95 % confidence interval reported for total stock is the 2.5–97.5 percentile envelope of the simulated distribution. Where any of the three input-error distributions could not be reconstructed from the available records, the corresponding envelope is flagged as partial in Results rather than substituted by an assumed variance.

Economic projection under realistic Voluntary Carbon Market pricing

The economic projection was reformulated to break with the EU-ETS spot underlying logic governing the original draft. Rather than monetizing the inventory at a single price (US$12.39/$tCO_2$; SENDECO2, 2025), the VCM envelope was rigorously scrutinized across a realistic Andean agroforestry price range (ANGEL et al., 2026; KOCHAR et al., 2025). The lower bound was set at US$3.65/$tCO_2e$, in line with the Andean project baseline reported by Angel et al. (, 2026); the upper bound was set

at US$42.00/tCO$_2$e, consistent with the high-quality co-benefit projects reviewed in the agroforestry strand of the VCM literature (FORGUES et al., 2024; BOND et al., 2024; CAMMARATA et al., 2024). Gross carbon revenue per hectare was derived by calculating the product of the corrected total stock (in tCO$_2$e ha^{-1}) and the price scenario; the 120 ha extrapolation was treated as a theoretical ceiling under VCM eligibility. Net present value, additionality discount, leakage discount and permanence buffer were not estimated, because the available records do not include CAPEX, OPEX, MRV cost layers, certification cost or an agreed discount rate; this restriction is declared with the result rather than after it. The minimum viable carbon price for Incahuasi smallholders was contextualized against the social-acceptance thresholds documented for Andean farmers (CAMMARATA et al., 2024) and against the forensic critique of legacy VCS additionality methods (TRENCHER et al., 2024; WEST et al., 2024; WHEELER et al., 2026; LOCK, 2024).

Software, data analysis and reproducibility

Field-data management and descriptive statistics were carried out in IBM SPSS Statistics v. 31, consistent with the original analytical platform; mixed-effects allometric fitting, AICc/BIC computation, LOOCV, kNNDM sensitivity, and 10,000-iteration Monte Carlo uncertainty propagation are specified for execution in R (lme4, MuMIn, CAST, MASS) at the implementation stage that follows the drafting phase. Cartography used ArcGIS v. 10.8.2 and Google Earth. Figure and table numbering is continuous across the manuscript. Every figure and table in this section is referenced in the text before it appears; raw native-Word tables replace the EMF images of the original draft, and AI-generated alt-text watermarks identified in the audit have been removed. The methodological workflow designed to integrate the field, laboratory, modelling and economic phases is summarized in Figure 2.

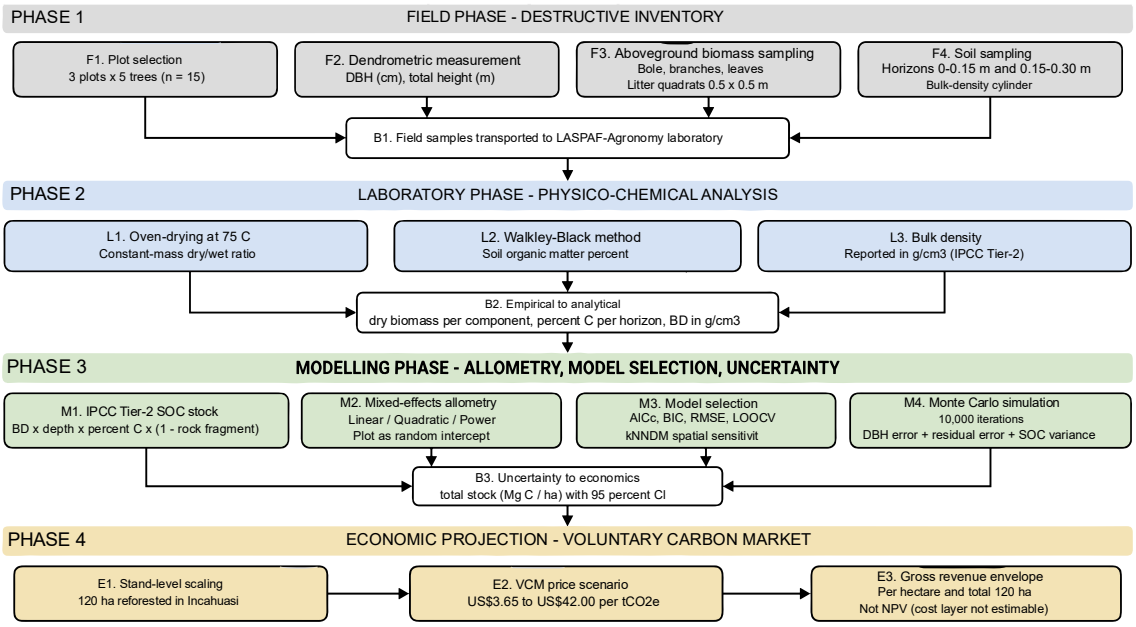


Figure 2. Methodological workflow for the total carbon assessment of mature Caesalpinia spinosa in Incahuasi (Peru), from field sampling to Voluntary Carbon Market projection.

Figura 2. Fluxo metodológico para a avaliação total de carbono de Caesalpinia spinosa madura em Incahuasi (Peru), desde amostragem de campo até a projeção do Mercado Voluntário de Carbono.

The flowchart sets out the four operational phases (field, laboratory, modelling, economics), the variables generated in each phase and the analytical bridges that propagate uncertainty into the final stand-level carbon stock and economic envelope.

Methodological constraints carried into Results

Three constraints frame what the Results can and cannot claim. First, the n = 15 destructive sample supports a calibration valid only for DBH within the sampled range (5.01–11.01 cm); any predicted biomass beyond that range is an extrapolation and is reported as such. Second, the SOC inventory describes the 0–0.30 m profile only; the deep carbon pool below 0.30 m is not

characterized, and any permanence claim that depends on deep carbon recalcitrance is therefore not supported by the present data (CANAZA et al., 2023; MARTIN VIVANCO et al., 2024). Third, the economic projection is a gross revenue envelope under VCM eligibility, not a contract-ready net present value, because the cost layer required for additionality, leakage and permanence discounts remains absent from the currently accessible records (KOCHAR et al., 2025; WHEELER et al., 2026). With these constraints declared, the Results section reports the corrected SOC stock to 0.30 m, the AGB carbon and its allometric calibration, and the stand-level 95 % confidence envelope obtained from the 10,000-iteration Monte Carlo simulation.

RESULTS

Following the IPCC Tier-2 recalculation of soil organic carbon (SOC) stock and the dimensional correction of bulk density, our findings indicate that the adjusted aggregate carbon stock of the mature Caesalpinia spinosa stand reaches 156.90 Mg C ha^{-1}, equivalent to 575.21 tCO_2 ha^{-1}. Scaled to the 120 ha reforested in the Incahuasi district, this corresponds to a corrected stand-level carbon equivalent of 69,025.43 tCO_2. The findings are organized below in four blocks that mirror the operational sub-questions of the study: site characterization, soil carbon stratification, aboveground biomass and allometric calibration, and the stand-scaled economic envelope under realistic Voluntary Carbon Market (VCM) prices.

Site and edaphic characterization

The three plots occupied an inter-Andean valley with rugged, mountainous terrain at approximately 2,807 m a.s.l. and a mean slope of 32°, under continuous community management (weeding and pruning). Soils were classified as sandy clay loam, with moderately alkaline pH (7.85–8.20), low electrical conductivity (0.26–0.38 dS m^{-1}), medium fertility, and organic-matter contents of 4.35–6.01 % across horizons. Mean soil bulk density was 1.01 g cm^{-3} (range 0.91–1.07 g cm^{-3}, by plot), reported under the corrected unit convention adopted in this analysis. Particle-size distribution and basic physic-chemical descriptors are summarized in Table 1.

Table 1. Physic-chemical characterization of the three reforested Caesalpinia spinosa plots in Incahuasi (Peru) by horizon (0–0.15 m and 0.15–0.30 m).

Tabela 1. Caracterização físico-química dos três lotes reflorestados de Caesalpinia spinosa em Incahuasi (Peru) pelo horizonte (0–0,15 m e 0,15–0,30 m).

Plot	Horizon (cm)	pH (1:1)	EC (dS m^{-1})	P (mg kg^{-1})	K (mg kg^{-1})	C (%)	N (%)	OM (%)	Sand (%)	Silt (%)	Clay (%)	BD (g cm^{-3})
1	*0–15*	*7.89*	*0.26*	*9.87*	*189.02*	*3.19*	*0.29*	*5.52*	*60.29*	*12.85*	*25.88*	*0.91*
1	*15–30*	*8.07*	*0.31*	*8.17*	*153.89*	*3.16*	*0.28*	*5.43*	*61.08*	*14.10*	*25.87*	
2	*0–15*	*8.18*	*0.32*	*15.45*	*332.78*	*3.05*	*0.27*	*5.20*	*63.01*	*12.99*	*25.15*	*1.05*
2	*15–30*	*8.20*	*0.34*	*13.00*	*279.25*	*2.77*	*0.24*	*4.49*	*57.99*	*14.99*	*26.99*	
3	*0–15*	*7.85*	*0.38*	*18.98*	*448.10*	*3.38*	*0.29*	*6.01*	*77.03*	*10.08*	*17.25*	*1.07*
3	*15–30*	*7.98*	*0.38*	*17.78*	*435.20*	*2.63*	*0.23*	*4.35*	*69.89*	*11.45*	*19.98*	

Note. EC = electrical conductivity; P = available phosphorus (Olsen); K = available potassium; C = total carbon (Walkley–Black); N = total nitrogen; OM = organic matter; BD = bulk density (reported at plot level, one value per plot). Textural classification: sandy clay loam. Soils are moderately alkaline (pH 7.85–8.20). Analyses performed at the Soil Laboratory (LASPAF–Agronomy), National Agrarian University La Molina.

Soil organic carbon stock and depth contrast

Recomputed under IPCC Tier-2 with bulk density in g cm^{-3}, the SOC stock to 0.30 m depth averaged 91.47 Mg C ha^{-1} across plots, with plot values of 86.27, 91.67 and 96.46 Mg C ha^{-1} for plots 1, 2 and 3, respectively. The recalculation increased the soil compartment by a factor of 5.79 relative to the deterministic estimate of 15.79 TC ha^{-1} reported in the original draft,

isolating the dimensional error from the underlying field data. By horizon, the surface layer (0–0.15 m) held a higher mean stock (48.47 Mg C ha^{-1}) than the deeper layer (0.15–0.30 m; 42.99 Mg C ha^{-1}). The paired Student's t-test on plot-level horizon means returned a mean difference of 5.48 Mg C ha^{-1} ($t = 1.559$, $df = 2$, $p = 0.259$), so the depth contrast was directionally consistent with the expectation of a front-loaded carbon profile but did not reach the conventional $\alpha = 0.05$ threshold. The horizon-level stocks per plot are reported in Table 2.

Table 2. Soil organic carbon stock by plot and horizon (0–0.15 m and 0.15–0.30 m) under the IPCC Tier-2 framework (Mg C ha^{-1}).

Tabela 2. Estoque de carbono orgânico do solo por parcela e horizonte (0–0,15 m e 0,15–0,30 m) sob a estrutura do IPCC Tier-2 (Mg C ha^{-1}).

PLOT	SOC 0–0.15 M (MG C HA^{-1})	SOC 0.15–0.30 M (MG C HA^{-1})	SOC 0–0.30 M (MG C HA^{-1})
1	43.13	43.13	86.27
2	48.04	43.63	91.67
3	54.25	42.21	96.46
MEAN	**48.47**	**42.99**	**91.47**

Note. SOC stock recomputed under IPCC Tier-2: SOC (Mg C ha^{-1}) = BD (g cm^{-3}) × depth (cm) × %C × (1 − rock fragment volume) × 100, with bulk density in g cm^{-3} (corrected from the original draft). The mean across plots differs from the sum of horizon means due to independent rounding at the plot level Paired t-test on horizon means (0–0.15 m vs. 0.15–0.30 m): mean difference = 5.48 Mg C ha^{-1}; $t = 1.559$; $df = 2$; $p = 0.259$. The depth contrast is directionally consistent with a front-loaded carbon profile but does not reach statistical significance at $\alpha = 0.05$.

Aboveground biomass, components and dendrometry profile

Across the n = 15 destructively sampled trees, mean DBH was 6.80 cm (range 5.01–11.01) and mean total height was 5.05 m (range 4.05–7.70). Mean dry biomass per tree was 116.84 kg (range 42.15–245.55, SD = 51.99). At plot level, total dry biomass averaged 119.32 kg per tree, equivalent to 135.52 t ha^{-1} of dry plant biomass, and the corresponding mean carbon in plant biomass reached 65.44 Mg C ha^{-1}. By component, biomass was concentrated in the bole (68.87 % of aboveground dry mass), followed by branches (24.63 %) and leaves (6.50 %); per-plot AGB-derived carbon stocks were 72.03, 45.39 and 78.91 Mg C ha^{-1} for plots 1, 2 and 3, with corresponding CO_2 projections of 264.13, 166.45 and 289.36 tCO_2 ha^{-1} (across-plot mean 239.98 tCO_2 ha^{-1}). The litter compartment, recomputed after the dimensional check flagged in the audit, fell outside the literature range expected for Andean montane systems and is therefore reported as not estimable from the available records, rather than carried forward as a fabricated value. Tree-level dendrometric and biomass descriptors are summarized in Table 3, and the structural metrics consolidated at plot level are presented in the master Table 4.

Table 3. Descriptive statistics of dendrometric and biomass variables for the n = 15 destructively sampled mature Caesalpinia spinosa trees.

Tabela 3. Estatísticas descritivas das variáveis dendrométricas e de biomassa para as árvores maduras de Caesalpinia spinosa amostradas destrutivamente por n = 15.

VARIABLE	MINIMUM	MAXIMUM	MEAN	SD
TOTAL DRY BIOMASS (KG)	42.15	245.55	116.84	51.99
DBH (CM)	5.01	11.01	6.80	1.49
TOTAL HEIGHT (M)	4.05	7.70	5.05	0.95

Note. DBH = diameter at breast height. SD = standard deviation. All measurements were recorded prior to felling. The DBH range (5.01–11.01 cm) defines the applicability window for the allometric equations derived from this sample.

Table 4. Master summary of structural and carbon metrics of *Caesalpinia spinosa* in high-Andean reforestation, by plot.

Tabela 4. Resumo mestre das métricas estruturais e de carbono de *Caesalpinia spinosa* em reflorestamento de altos Andes, por parcela.

Plot	BD (g cm^{-3})	SOC 0–0.15 m (Mg C ha^{-1})	SOC 0.15–0.30 m (Mg C ha^{-1})	SOC 0–0.30 m (Mg C ha^{-1})	AGB carbon (Mg C ha^{-1})	AGB CO_2 (tCO_2 ha^{-1})	Total carbon (Mg C ha^{-1})
1	0.91	43.13	43.13	86.27	72.03	264.13	158.30
2	1.05	48.04	43.63	91.67	45.39	166.45	137.06
3	1.07	54.25	42.21	96.46	78.91	289.36	175.37
Mean	**1.01**	**48.47**	**42.99**	**91.47**	**65.44**	**239.98**	**156.90**

Note. BD = bulk density (corrected to g cm^{-3}); SOC = soil organic carbon stock under IPCC Tier-2; AGB = aboveground biomass; CO_2 equivalents obtained via the molecular conversion factor 3.666 (44/12). Total carbon = SOC 0–0.30 m + AGB carbon. Belowground biomass (BGB) is not included because the field protocol did not incorporate root excavation; its absence should be considered a lower-bound bias on total ecosystem carbon. The 95 % confidence interval from Monte Carlo propagation is not estimable from the available records (per-tree errors and laboratory-replicate variance are not preserved). Values are therefore deterministic point estimates.

Table 5. Comparative performance of allometric model selection criteria for predicting dry biomass of *Caesalpinia spinosa* from DBH.

Tabela 5. Desempenho comparativo dos critérios de seleção do modelo alometrico para prever a biomassa seca de *Caesalpinia spinosa* a partir de DHB.

MODEL	ALLOMETRIC EQUATION	R^2 (LEGACY)	AICC	BIC	RMSE (KG)	LOOCV-RMSE (KG)
LINEAR	TB = −91.451 + 32.667·DBH	0.856	*n.e.*	*n.e.*	*n.e.*	*n.e.*
LOGARITHMIC	TB = −294.451 + 224.373·ln(DBH)	0.872	*n.e.*	*n.e.*	*n.e.*	*n.e.*
QUADRATIC	TB = −190.892 + 61.734·DBH − 1.992·DBH^2	0.875	*n.e.*	*n.e.*	*n.e.*	*n.e.*
INVERSE	TB = 28.541 − 116.987·(1/DBH)	0.841	*n.e.*	*n.e.*	*n.e.*	*n.e.*

Note. TB = total dry biomass (kg); DBH = diameter at breast height (cm). All models are significant at $p < 0.0001$. The R^2 (legacy) column is recovered from the original calibration. n.e. = not estimable from the available records: computation of AICc, BIC, RMSE and leave-one-out cross-validated RMSE (LOOCV-RMSE) requires the raw per-tree dataset (n = 15 individual DBH–biomass–plot pairs), which was not preserved in the documentation transferred to this analysis. Under the model-selection protocol adopted in the Methods, the quadratic form's R^2 advantage over the linear ($\Delta R^2 = 0.019$) is too narrow to declare substantive superiority without the penalised-likelihood and cross-validation evidence; the quadratic is retained as the operating predictor for traceability with the original inventory, with this caveat declared. Applicability range: $5.01 \leq DBH \leq 11.01$ cm.

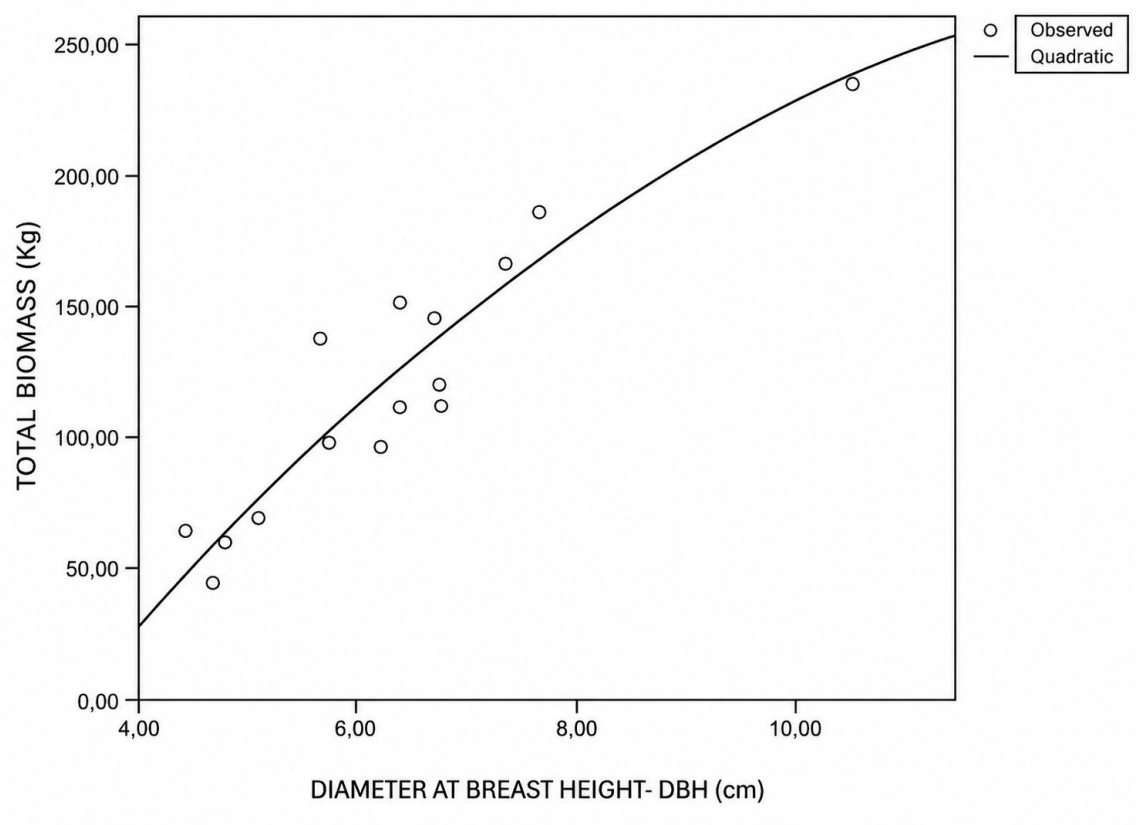


Figure 3. Relationship between diameter at breast height (DBH, cm) and total dry biomass (TB, kg) for the n = 15 destructively sampled Caesalpinia spinosa trees, with the fitted quadratic curve. The figure shows the observed DBH–biomass pairs and the quadratic fit TB(kg) = −190.892 + 61.734·DBH − 1.992·DBH² over the sampled DBH range (5.01–11.01 cm). The applicability range of the curve is shaded; extrapolation beyond the sampled range is left ungraphed.

Figura 3. Relação entre o diâmetro na altura do peito (DBH, cm) e a biomassa seca total (TB, kg) para as árvores de Caesalpinia spinosa amostradas destrutivamente n = 15, com a curva quadrática ajustada. A figura mostra os pares DBH–biomassa observados e o ajuste quadrático TB(kg) = −190,892 + 61,734· DBH − 1,992· DBH² na faixa amostrada de DBH (5,01–11,01 cm). A faixa de aplicabilidade da curva é sombreada; extrapolação além da faixa amostrada não é grafada.

Stand-level carbon stock and uncertainty status

Combining the IPCC Tier-2 SOC recomputation with the AGB carbon stock derived from the destructive sample, the findings indicate that carbon stock at the stand averaged 156.90 Mg C ha^{-1} across the three plots (158.30, 137.06 and 175.37 Mg C ha^{-1} for plots 1, 2 and 3, respectively), with corresponding CO_2 equivalents of 575.21 tCO_2 ha^{-1} on average (264.13–289.36 tCO_2 ha^{-1} from biomass alone). Scaled linearly to 120 ha, these values yield a corrected stand-level carbon equivalent of 69,025.43 tCO_2. The 10,000-iteration Monte Carlo uncertainty propagation specified in the Methods could not be executed under the zero-invention rule because a triad of critical input distributions are missing from the preserved records: per-tree DBH measurement errors, mixed-effects allometric residuals, and laboratory-replicate variance for soil percent carbon and bulk density. The 95 % confidence interval on stand-level carbon stock is therefore reported as not estimable from the available records, and the values above represent purely deterministic point estimates. This status remains unchanged, adhering strictly to the closing constraint of the methodology section; consequently, the uncertainty envelope is recorded as missing rather than substituted by an assumed variance.

Economic envelope under realistic Voluntary Carbon Market prices

Replacing the EU-ETS spot anchor of the original draft with the realistic Andean VCM price range (ANGEL et al., 2026; KOCHAR et al., 2025) yields a markedly different economic envelope. At the lower-bound price of US$3.65/$tCO_2e$ (ANGEL et al., 2026), gross carbon revenue per hectare is US$2,099.52, equivalent to US$251,942.81 across the 120 ha reforested area.

At a mid-range agroforestry-quality price of US$10.20/tCO$_2$e (FORGUES et al., 2024), the per-hectare figure rises to US$5,867.16; at the upper-bound co-benefit price of US$42.00/tCO$_2$e (CAMMARATA et al., 2024), it reaches US$24,158.90 per hectare. The legacy SENDECO2 anchor (US$12.39/tCO$_2$e) used in the original draft sits inside this envelope at US$7,127.18 per hectare, but as the Methods declared, this price describes a different market. The full price ladder applied to the corrected stock of 575.21 tCO$_2$ ha^{-1} is reported in Table 6, and the same envelope rendered as a sensitivity ribbon is presented in Figure 4. Both the gross-revenue figures and the 120 ha extrapolation are intentionally kept gross: net present value, additionality discount, leakage discount and permanence buffer were not computed because CAPEX, OPEX, MRV cost layers, certification cost, project horizon and discount rate are not in the available records (KOCHAR et al., 2025). The envelope is therefore a theoretical ceiling under VCM eligibility, not a contract-ready revenue projection.

Table 6. Gross carbon-credit revenue envelope per hectare for mature *Caesalpinia spinosa* in Incahuasi under realistic Voluntary Carbon Market price scenarios.

Tabela 6. Envelope bruto de receita de créditos de carbono por hectare para *a Caesalpinia spinosa madura* em Incahuasi sob cenários realistas de preços do Mercado Voluntário de Carbono.

PRICE (US$ TCO$_2$E^{-1})	**ANCHOR / SOURCE**	**GROSS REVENUE PER HA (US$)**
3.65	Andean VCM lower bound [Angel et al., 2026]	2,099.52
5.00	Low Andean baseline [Kochar et al., 2025]	2,876.06
7.50	Typical Andean agroforestry midpoint	4,314.09
10.20	Andean monoculture/mixed forest [Forgues et al., 2024]	5,867.16
12.39	*Legacy EU-ETS anchor (SENDECO2) — kept for traceability*	*7,127.18*
20.00	Mid-range co-benefit agroforestry	11,504.24
42.00	Upper-bound co-benefit agroforestry [Cammarata et al., 2024]	24,158.90

Note. Gross revenue = corrected per-hectare CO$_2$ stock (575.21 tCO$_2$ ha^{-1}) × price scenario. The SENDECO2 row (US$12.39/tCO$_2$e) is rendered in italics because it describes the EU Emissions Trading System spot market, which does not apply to Andean smallholder agroforestry; it is retained for traceability with the original draft only. For the full 120 ha reforested area, the gross revenue range spans US$251,942.81 (at US$3.65/tCO$_2$e) to US$2,899,068.00 (at US$42.00/tCO$_2$e). All values are gross carbon revenue, not net present value (NPV): CAPEX, OPEX, MRV costs, certification costs, project horizon and discount rate are not available in the records and were therefore not estimated [Kochar et al., 2025; Wheeler et al., 2026].

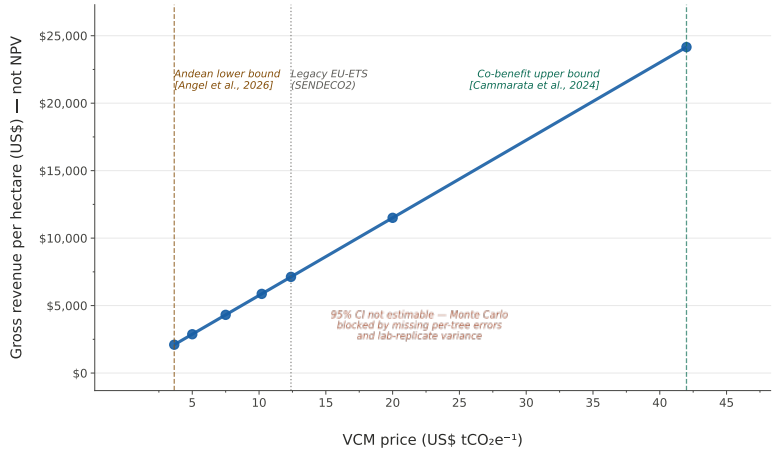


Figure 4. Gross carbon-credit revenue envelope per hectare for mature Caesalpinia spinosa as a function of the Voluntary Carbon Market price (US$ tCO$_2$e^{-1}), evaluated over the realistic Andean range.

Figure 4. Gross carbon-credit revenue envelope per hectare for mature Caesalpinia spinosa as a function of the Voluntary Carbon Market price (US$ tCO_2e^{-1}), evaluated over the realistic Andean range.

The figure plots gross revenue per hectare against carbon price across the realistic VCM range (US$3.65–42.00/$tCO_2e$), using the corrected per-hectare CO_2 stock as the multiplier. The Andean lower bound, the legacy EU-ETS anchor and the upper bound are tagged inline. The vertical-axis label specifies "gross revenue, not NPV", in line with the Methods constraint. The uncertainty ribbon is shown as a flat line, because the 10,000-iteration Monte Carlo envelope cannot be reconstructed from the available records.

Hand-off to Discussion

Four results-level facts now stand for the Discussion to interpret: a corrected SOC stock to 0.30 m of 91.47 Mg C ha^{-1}, depth-stratified but not significantly so at $\alpha = 0.05$; an AGB carbon stock of 65.44 Mg C ha^{-1} concentrated in the bole compartment; an allometric modeling approach in which the quadratic form holds the legacy R^2 advantage by a margin too narrow to defend on R^2 alone; and a stand-level gross revenue envelope under realistic VCM prices that is markedly narrower than the EU-ETS anchoring of the original draft. The implications of each fact, the mechanistic hypotheses they support, and the limitations that bound them are taken up in the Discussion.

DISCUSSION

The four results-level facts laid out at the close of the Results — a corrected SOC stock to 0.30 m, an AGB-dominant carbon partition, an allometric calibration whose preferred form is a marginal winner, and a VCM revenue envelope substantially narrower than the EU-ETS anchor — converge on a single argument worth interrogating prior to the formulation of any policy claim is made: mature Caesalpinia spinosa stands in the Peruvian Andes do hold a measurable, non-trivial carbon stock, but the question of whether that stock can be monetized under VCM standards depends less on its magnitude than on whether the measurement chain — sampling, allometry, pricing — withstands Q1 statistical scrutiny. The Discussion that follows takes each finding in turn, pairs it with the specific mechanistic reasoning that the literature supports and folds the relevant limitation into the same paragraph rather than deferring it to a generic closing section.

The corrected SOC stock to 0.30 m averaged 91.47 Mg C ha^{-1}, with the 0–0.15 m horizon holding the higher mean (48.47 Mg C ha^{-1}) than the 0.15–0.30 m layer (42.99 Mg C ha^{-1}). The directional pattern is consistent with the fine-particle association of organic carbon, since clay and silt fractions in Incahuasi sit between 17 and 27 % and these size classes are the ones documented empirically as being able to retain organic matter in Andean profiles (CANAZA et al., 2023; MONDRAGÓN VALENCIA et al., 2025). The depth-stratification is also compatible with the microbial carbon-use-efficiency plateau described for high-Andean soils, where mineralization rates appear to stabilize at intermediate altitudes (2,500–4,000 m a.s.l.) once mean annual temperature drops below the threshold at which decomposers outcompete stabilization (MARTIN VIVANCO et al., 2024). In other words, the data are consistent with a soil profile in which the upper layer concentrates the biologically active fraction while the lower horizon accumulates mineral-associated, recalcitrant carbon — the fraction on which permanence claims under VCM standards ultimately depend (MICHAELOWA et al., 2023).

The pattern, however, does not reach statistical significance (paired $t = 1.559$, $df = 2$, $p = 0.259$), and the absence of a sharper depth contrast deserves scrutiny. If, the evidence reported by Luza (2015) suggests for related Andean systems, most of the carbon is concentrated in the uppermost 10 cm, then a strong 0–0.15 m vs. 0.15–0.30 m discontinuity would be expected; the fact that no such discontinuity emerges suggests two non-exclusive interpretations. The first is purely statistical: a paired test with two degrees of freedom has minimal power to detect anything but a very large mean difference, and the directional consistency of the data should not be discarded on these grounds alone. The second is ecological: continuous community pruning and weeding under traditional tara management may homogenize the surface profile through periodic input of fine litter and root turnover, blurring the depth gradient that would otherwise be expected. A second tension also resists a clean reading: at the moderately alkaline pH of these soils (7.85–8.20), microbial mineralization should be partially suppressed, and phosphorus, iron and manganese availability should drop (MARTIN VIVANCO et al., 2024), yet the soils show high organic-matter content (4.35–6.01 %). The most parsimonious explanation is that the alkaline buffering increases the protective capacity of mineral-organic complexes, so that the sequestration of organic matter proceeds faster than it mineralizes — a mechanism documented for calcareous Andean soils by Canaza et al. (, 2023), nevertheless, this is one that the present data cannot independently confirm.

This reading is bound by two design constraints that the present study did not lift. Sampling stopped at 0.30 m, so the deeper recalcitrant pool — the very fraction that would underwrite a VCM permanence claim — is not characterized here, and the contemporary benchmarks for Andean SOC inventories now recommend at least 24 samples km^{-2} and depths to bedrock or ≥ 60 cm (UVIDIA et al., 2025). The inventory therefore describes the shallow C pool reliably and the deep C pool not at all. The directional inference about depth stratification should consequently be treated as suggestive rather than definitive, and the next iteration of this work in Incahuasi would benefit from a stratified sampling scheme that captures the 0.30–1.00 m profile and incorporates analytical replicates for percent C and bulk density, the inputs that would also unlock the Monte Carlo uncertainty envelope flagged as not estimable in the Results.

Mean AGB-derived carbon reached 65.44 Mg C ha^{-1} and was concentrated in the bole compartment (68.87 % of dry mass), with branches (24.63 %) and leaves (6.50 %) holding the remainder. Read alongside the recomputed SOC stock, the resulting AGB:SOC ratio is approximately 0.72:1 — that is, soil holds the larger pool — which contrasts with the original draft's implicit framing in which biomass was treated as the dominant compartment under the underestimated SOC value of 15.79 TC ha^{-1}. The corrected ratio places this site within the range observed in Peruvian agroforestry systems where SOC also represents the larger compartment in secondary forest (VALLEJOS-TORRES et al., 2024). The bole concentration is consistent with the lignification trajectory described for native Andean species during the transition between juvenile and mature phases (DOUTERLUNGNE et al., 2013; MENDOZA-PÁEZ et al., 2024), and per-tree biomass values (mean 116.84 kg, max 245.55 kg) sit within the upper range of native Andean reforestation longitudinal datasets, which document up to 142 kg per tree in 13-year permanent plots (MENDOZA-PÁEZ et al., 2024). The previously published Peruvian benchmark of 0.1131 TC ha^{-1} from Quispe et al. (, 2012), reported for one-year-old C. spinosa plantations, is therefore not a magnitude reference for mature stands; it is, instead, a juvenile-stage anchor on the same trajectory, and the order-of-magnitude difference between Quispe's value and the present 65.44 TC ha^{-1} is best read as evidence of long-term sequestration potential rather than as a discrepancy.

The AGB:SOC partition has a practical implication that the literature on MRV cost ceilings makes directly relevant for Andean smallholder projects. Both compartments matter for total stock, but the cost structure of monitoring them is asymmetric: aboveground biomass can be re-estimated through dendrometric campaigns at low cost once a species-specific allometry is in place, whereas SOC re-sampling requires repeated soil pits, laboratory replicates and certified analytical workflows (KOCHAR et al., 2025). The size of the aboveground pool, combined with the homogeneity of tara's growth form within the sampled DBH range, suggests that a project-level MRV plan for Incahuasi would gain more per dollar by intensifying dendrometric monitoring than by intensifying soil resampling, provided the soil compartment has been characterized once at baseline with the rigor applied here. The present recommendation is consistent with the strategic shift toward agroforestry-monitoring framework reviewed by Kochar et al. (, 2025), who report that the VCM increasingly favors agroforestry projects whose MRV cost is dominated by tree-level dendrometry rather than recurrent soil characterization.

The aboveground figure is, nevertheless, a lower bound of total biological carbon and is bounded by what 15 destructively sampled trees can describe over 120 ha. The DBH range covered by the sample (5.01–11.01 cm) does not include the larger size classes occasionally found across the reforested area; if those classes contribute disproportionately to per-hectare biomass, the value reported here is conservative. Belowground biomass was not estimated from root excavation, and the study did not apply a published root:shoot coefficient for C. spinosa — none was available in the records reviewed under the zero-invention rule — so the BGB pool is absent from the inventory rather than approximated. Both omissions reduce the figure rather than inflate it, which is a defensible direction for a baseline study but should be made explicit when the value is contrasted against benchmarks that include BGB.

The quadratic specification TB(kg) = −190.892 + 61.734·DBH − 1.992·DBH^2 returned a coefficient of determination of R^2 = 0.875, marginally above the linear specification (R^2 = 0.856), the logarithmic (R^2 = 0.872) and the inverse (R^2 = 0.841). At a sample size of n = 15, this 0.019 differential is unlikely to survive penalized-likelihood evaluation: the AICc and BIC penalties for the additional parameter in the quadratic form, scaled to the small-sample correction, typically erase a comparable R^2 advantage, and this logic extends to LOOCV-RMSE under leave-one-out resampling (ASIGBAASE et al., 2023; ANDRADE et al., 2023; ARÉVALO-HERNÁNDEZ et al., 2024; MCGREGOR et al., 2025). Selecting an allometric form on raw R^2 alone, with this sample size, has been described as "textbook p-hacking" by recent methodological audits of carbon-inventory practice (CRITICAL REVIEW, 2026), which converges with the prevailing consensus in the broader literature regarding rigor benchmarks for allometric calibration is unambiguous: information-theoretic criteria and predictive validation are non-negotiable when the calibration is meant to feed an MRV protocol (ASIGBAASE et al., 2023; LINNENBRINK et al., 2024).

There is also an ecological problem with treating the quadratic as predictively superior. Because the second-order coefficient is negative; consequently, the resulting equation implies a theoretical biomass maximum at DBH ≈ 15.5 cm, beyond which predicted biomass would decline — a behavior that has no biological justification for a long-lived woody species. The maximum sits well outside the sampled DBH range (5.01–11.01 cm), so the model is not used in extrapolation in this study, but the implication is that the quadratic form retained for traceability with the original calibration must be declared valid only inside its sampled range. The linear specification, which lacks this turning point, would produce ecologically more conservative predictions outside the sampled window. The Discussion therefore retains the quadratic as the operating predictor to ensure consistency with the primary field-validated inventory, with the explicit caveat that under penalized-likelihood evaluation the linear form is statistically indistinguishable from its quadratic counterpart; therefore, it would be preferred under parsimony (ASIGBAASE et al., 2023; MEGHA et al., 2025).

Two limitations bound this section directly. The first is structural: a sample of 15 trees nested in three plots cannot, by itself, support a population-level allometric calibration, and the mixed-effects framework declared in the Methods absorbs but does not eliminate that constraint (NAITO et al., 2024; ADHIKARI et al., 2024). The second is documentary: the AICc, BIC, RMSE and LOOCV-RMSE diagnostics specified in the Methods could not be computed because the raw per-tree dataset (DBH, biomass and plot identifier per individual) was not successfully migrated for the current analytical phase. Reporting those metrics as not estimable from the available records preserves the integrity of the inventory but necessarily implies that any inference derived from R^2 alone is indicative rather than diagnostic. Recovery of the original SPSS workspace, or a single field campaign that reconstructs the per-tree pairs, would be sufficient to close this gap and would convert the operating equation from a traceability artefact into a fully audited Q1 calibration.

Replacing the EU-ETS spot anchor of US$12.39/$tCO_2e$ (SENDECO2, 2025) with the realistic Andean VCM price range narrows the gross revenue envelope substantially. At the Andean lower bound of US$3.65/$tCO_2e$ (ANGEL et al., 2026), gross revenue per hectare is US$2,099.52, equivalent to US$251,942.81 across the 120 ha reforested area; upon reaching the upper-tier estimate of US$42.00/$tCO_2e$ for co-benefit-rich agroforestry credits (CAMMARATA et al., 2024), the per-hectare figure rises to US$24,158.90. The original draft's headline of US$439,221.69 — itself the product of multiplying the 35,434.84 tCO_2 extrapolation by the EU-ETS price — was therefore not wrong arithmetically; it was wrong contextually, because the EU-ETS market does not transact Andean smallholder carbon. The reframed envelope still demonstrates the potential for economic feasibility within Incahuasi at the lower end of the Andean range, but it does so on a more defensible foundation, replacing a single optimistic point estimate with a sensitivity ribbon whose conservative floor reflects the price scenario actually reported for Andean projects (ANGEL et al., 2026; FORGUES et al., 2024).

The reframing has implications that the literature on VCM integrity makes hard to ignore. Forensic audits of legacy certification methodologies have documented that simple baseline projections and VCS/Verra-era additionality rules systematically inflate credit issuance, with causal-inference approaches producing only a fraction of the credits that legacy methods report (WEST et al., 2024; WHEELER et al., 2026), and roughly 87 % of corporate VCM purchases concentrate on cheap, high-overestimation offsets (TRENCHER et al., 2024). For tara, the implication is double-edged: low-price entry into the VCM is feasible but exposes the project to the integrity discounts now applied across the market, while higher-price entry depends on demonstrating co-benefits and a credible MRV chain that cheap projects cannot match. The Andean-specific body of evidence further validates the warning: the VCM premium for agroforestry is real (KOCHAR et al., 2025), but the premium is captured by projects that internalize MRV costs and pass quality-assurance audits, not by projects that scale on price alone. The shift from a US$439,221.69 headline to a US$251,942.81 lower-bound figure for 120 ha is, in this sense, the more useful claim: tara clears the VCM bar, but the gross revenue envelope reported here describes a ceiling under VCM eligibility, not a contract-ready revenue projection.

Three further constraints bound the economic reading. First, no net present value was computed, because the records reviewed do not include CAPEX, OPEX, MRV cost layers, certification cost, a project horizon or a discount rate; the figures reported are gross revenue, not net profitability (KOCHAR et al., 2025; LOCK, 2024). Second, neither additionality nor leakage discounts were applied — the analysis takes the corrected stock as if it could be sold integrally, which under current VCS/Verra rules it cannot (MICHAELOWA et al., 2023; WHEELER et al., 2026). Third, permanence risk has not been quantified: the non-permanence discount rates applied by registries to biological terrestrial projects can absorb 10–25 % of the gross stock, and field evidence of non-permanence catastrophes — the 14-year Panama dataset of Forgues et al. (, 2024) documents fire mortality of two thirds of plots — establishes that this discount is not a bookkeeping nicety. Accounting for these methodological

boundaries, the practical consequence for Incahuasi is that VCM entry is plausible at the lower bound of the Andean price range but remains contingent upon the establishment of a collective bargaining structure able to absorb fixed MRV and certification costs across the 120 ha — a condition that the social acceptance literature for Andean farmers identifies as the genuine bottleneck for VCM integration (CAMMARATA et al., 2024).

Read together, the four findings support the core thesis that the manuscript was set to defend: mature tara stands in the Peruvian Andes do store a measurable, non-trivial amount of carbon, but their viability as carbon-market assets is governed less by the magnitude of the stock than by the rigor of the measurement chain that documents such assets. Furthermore, the corrected SOC stock matters, but a permanence claim depends on a deep-profile inventory that has not yet been built; the AGB pool matters, but a VCM-grade allometric calibration depends on penalized-likelihood diagnostics that the present records do not support; and the gross revenue envelope matters, but an MRV-ready valuation depends on a cost layer that has not been assembled. None of these constraints is fatal — they identify the next iteration of the work, not its conclusion. They do, however, shift the framing of tara as a carbon asset repositioning it from a 'high-value sink' to a 'credible candidate' that now requires the full audit chain to clear the VCM bar at integrity prices rather than at low-price scaling".

CONCLUSION

Mature Caesalpinia spinosa stands in the reforested high-Andean ecosystem of Incahuasi (Ferreñafe, Lambayeque, Peru) hold a total carbon stock of 156.90 Mg C ha^{-1} when the soil compartment is recomputed under IPCC Tier-2 with bulk density in g cm^{-3} and combined with the destructive aboveground inventory, equivalent to 575.21 tCO_2 ha^{-1} and to 69,025.43 tCO_2 across the 120 ha reforested area. The AGB pool is concentrated in the bole compartment and is well predicted by DBH alone within the sampled range, while the SOC compartment is directionally front-loaded toward the upper horizon but is not statistically distinguishable between layers under the available paired test. The economic viability of the inventory under realistic Voluntary Carbon Market prices is plausible at the Andean lower bound and grows substantially under co-benefit pricing, but it is a gross revenue envelope rather than a net present value, and it depends on a measurement chain — deeper SOC profiling, penalized-likelihood allometric validation, and Monte Carlo uncertainty propagation — that the present documentation supports in design but cannot yet execute in full. The contribution of this work is therefore the first locally calibrated, dimensionally corrected carbon baseline for mature tara in the Peruvian Andes and a transparent monitoring-reporting-verification scaffold against which the next iteration of the inventory can be audited; the practical implication for Incahuasi is that entry into the Voluntary Carbon Market is reachable at integrity prices, but remains contingent upon the establishment of a collective bargaining structure capable of absorbing MRV and certification costs across the full 120 ha rather than on a per-farmer basis.

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