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Carbon balance, canopy spatial structure and renovation benchmarks in old cocoa agroforestry systems of the Dominican Republic

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Abstract

Rehabilitation and renovation (Rh/Re) are essential elements in the cocoa cultivation cycle. Cocoa farmers must decide on whether to rehabilitate (Rh) or to renovate (Re) a cocoa orchard when its productivity declines due to ageing, disease outbreaks or other causes. Cocoa Rh/Re interventions alter standing biomass while retaining variable amounts of old canopy, roots and soil carbon. We quantified carbon stocks and structural attributes across a 52-farm project frame in in two growing regions in the Dominican Republic using 40 vegetation inventories, 50 soil records, 26 preparation-site intervention records and 25 matched inventory–intervention pairs. Above-ground biomass was estimated with diameter-compatible allometry; woody roots and 0–15 cm soil carbon was accounted for separately. Mean live-biomass stock was 192.63 ± 34.21 Mg CO_2e ha^{-1} (n = 40) and mean live-plus-soil stock was 306.60 ± 36.45 Mg CO_2e ha^{-1} for 38 farms with linked soil data. In matched farms, estimated preparation-site above-ground removal averaged 93.72 ± 11.44 Mg CO_2e ha^{-1}, which is almost half of the above-carbon stocks. Group-specific Clark–Evans spatial indices, vertical structure and soil latent factors were integrated at farm level. Across all farms, 21 total-stem arrangements (cacao + companion trees) were classified as aggregated, 16 as approximately random and 3 as regular. Finally, a fixed 35-year renovation scenario produced 73.94 Mg CO_2e ha^{-1} of new cocoa and boundary-tree stock, 19.78 Mg CO_2e ha^{-1} below the mean removal proxy suggesting that Rh/Re interventions do not compensate for the above-ground carbon removed from target cacao orchards. This study provides a reproducible plot-level accounting framework for Rh/Re implementation while distinguishing measured stocks, removed above-ground stocks, residual below-ground reserves and future regrowth and carbon sequestration scenarios.

Keywords: *Theobroma cacao*; agroforestry renovation; biomass carbon; spatial structure; soil organic carbon; Dominican Republic.

1 Introduction

Cocoa agroforestry systems combine a perennial crop with shade, fruit and timber trees, and their carbon stocks therefore depend on stand composition, age, management and land-use history (Somarriba et al., 2013, Asare et al., 2017, Cornelius et al., 2024). Regional studies show that companion-tree abundance and arrangement can substantially influence woody carbon stocks and cocoa performance, while comparisons among systems require explicit and consistent carbon pools and system boundaries (Somarriba et al. 2013; Notaro et al. 2021; Suárez et al. 2026b; Mora Garces et al. 2026). Recent guidance for carbon studies in Agroforestry Systems further stresses precise site description, transparent allometric methods, explicit stock terminology and careful separation of stocks from sequestration rates (Cornelius et al., 2025; Cardinale et al. 2025). Renovation creates an additional accounting challenge because pruning or felling can occur gradually while roots, soil carbon and part of the old canopy remain (Lori et al, 2017; Somarriba et al., 2021; Morales-Belpaire et al, 2025; Gama-Rodrigues et al, 2026).

Cocoa production in the Dominican Republic (DR) is predominantly based on **multistrata agroforestry systems**, in which cacao is cultivated under heterogeneous canopies composed of timber, fruit, leguminous, and other shade-tree species (Notaro et al., 2020; Notaro, 2021). Previous mapped agroforestry research showed four major agroforestry archetypes that exhibit substantial variation in canopy architecture, tree density, species composition, vertical stratification, and spatial arrangement, reflecting both biophysical conditions and farmers' management decisions. Studies conducted across major cocoa-producing areas indicate that DR cocoa agroforestry systems range from relatively simple shade associations to highly diversified shade canopies, providing important ecological and socioeconomic functions (Cerda et al., 2018; Notaro et al., 2020). At large, cacao agroforestry systems in the DR are typically +80 years old with a narrow cacao genetic background, poor fertilization and under traditional management, resulting in low annual productivity of 250-500 kg ha^{-1} (Brito Sosa, 2021, Notaro et al, 2022, Orozco et al., 2024).

At national level, official statistics advised that about 60% of the 150, 000 ha of current cultivated area in DR needs Rh/Re interventions (Fontagro, 2018; Comision Nacional de Cacao, 2020; GAIA, 2021; MAG, 2022). Old and unproductive cacao orchards, recurrent hurricanes and the availability of new technologies to increase crop yield (improved genetics, new grafting techniques, private and public incentives, etc.) have been the three major driving forces in Rh/Re initiatives in the DR. Cocoa agronomists have devised methods and protocols to help farmers to decide when and how to conduct Rh/Re of an old orchard, among these, the Turrialba method has been proposed to conduct Re on smallholders' farmers. The Turrialba method is a progressive cocoa-renovation strategy originally developed and evaluated at the Tropical Agricultural Research and Higher Education Center (CATIE), Turrialba, Costa Rica. Its central principle is to establish new, improved cocoa plants within an existing old cocoa plantation and progressively remove the old trees as the new cocoa canopy develops (Amores & Quiroz, 2002; Dallberg, 2015). The Turrialba method addresses one of the major constraints associated with conventional cocoa Re; the temporary loss of production and income following complete orchard removal. Its fundamental innovation is that the old cocoa orchard is not immediately considered an obstacle to Re; instead, it is temporarily incorporated into the transition by providing shade and residual production, while improved cocoa plants are established and the old canopy is progressively removed. Thus, the Turrialba method becomes an effective Re/Rh intervention metho among small scale cocoa farmers (Adeyemi 1999, Mattick 1999; Vaz, 1995).

Rh/Re interventions can simultaneously change productivity, canopy structure, and biomass reserves of dominant cocoa systems in the **DR** (Cerda et al., 2018; Notaro et al., 2021; Andrade et al., 2022). Therefore, jointly quantifying the stock and the potentially removable biomass is necessary to guide management decisions and establish a verifiable baseline. The central question of this study was how much standing carbon was present at the inventory date, how large the intervention-based above-ground removal proxy was, and how a specified replacement design compares with that proxy over 35 years. Specifically, we aimed to (i) estimate above-ground, and soil carbon stocks in targeted old cacao orchards; (ii) quantify an intervention-based above-ground removal proxy for matched preparation-site records; (iii) characterize diversity, vertical structure and cocoa versus companion spatial arrangement; and (iv) compare a fixed 35-year replacement-cohort trajectory with the mean intervention-based removal proxy as benchmark for carbon balance for conducting cacao Rh/Re interventions among small-scale farms.

2 Materials and methods

2.1 Study site, design and data coverage

Three main cocoa production areas located in the provinces of Duarte (19210 N; 70030 W), El Seibo (18770 N; 69100 W) and San Cristobal (18420 N; 70100 W) account for 42% of the Dominican cocoa cultivated area and for more than 70% of the national cocoa production (Deheuvels 2015; Fontagro, 2018, GAIA, 2021). They share similar average annual temperatures and precipitations, ranging from 19 to 32 C, and from 1600 to 1800 mm, respectively. Average soil conditions are favorable for cocoa production: 3.2% organic matter, pH 6.9, 0.3 meq K/100 mL, 18 ppm Ca, 4.3 ppm Mg, 10 ppm P, 8 ppm Zn and 2 ppm S (Dominguez 1983). The Re/Re project frame comprised 52 mapped farms across Arenoso, Castillo, Cotuí, the eastern zone, La Peña, Salcedo and San Francisco de Macorís, the northern zone. Forty farms had a cacao and shade tree inventory, 50 had a laboratory soil record, 26 had a preparation-site (PPC) record, and 25 could be matched between tree inventory and PPC by verified identifier; 23 of these pairs had linked soil data. Each shade canopy inventory covered a 20 × 50 m plot (0.1 ha), so plot totals were multiplied by ten to express stocks and densities per hectare (Somarriba et al., 2023; Deheuvels et al., 2014). The standing-stem inventory counted established cocoa retained during PCC and renovation. Newly replanted cocoa plants, less than 10 months old at the June 2026 inventory, were excluded from the established-biomass inventory. Exact correspondence between the intervention footprint and each 0.1-ha plot was not documented in the processed files.

2.2 Field variables and quality control

For each mapped cocoa farm and shade tree inventory records included, DAP (cm), tree total heigh, crown height, shape and width (m), taxon or field name, functional group (fruit, shade, timber, palms, other) and plot coordinates. Cocoa plants measured 30 cm above ground (D30) were kept separate from stems measured at breast height (DBH); multiple cocoa stems were combined as the square root of the sum of squared diameters. Wood density values were linked to registered shade trees where available. Taxa were harmonized without discarding their field names. Musaceae contributed aerial non-woody biomass and diversity records but received no estimated roots.

Soil data were analyzed as a separate laboratory dataset (n = 50); 38 inventory plots had matched 0–15 cm soil-stock estimates. Organic carbon was derived from organic matter using a factor of 1.72, and bulk density came from the documented pedotransfer function in the consolidated database (McBratney et al.

2002; Acutis & Donatelli, 2003, Budiman, 2007). We did not extrapolate the 0–15 cm observations to 0–30 cm or assign zero to missing records. Measured bulk density, coarse-fragment corrections, the number of cores and the compositing pattern per farm were not fully documented in the available processed files.

2.3 Biomass and carbon-equivalent estimation

Individual above-ground dry biomass was converted to carbon using a fraction of 0.47 for field stocks and then to CO_2 equivalent by multiplying carbon by 44/12 (. For DBH-based cocoa, coffee and shade trees, local height–diameter relations were embedded in the Chave et al. (2014) equation; shade-tree wood density used species-specific or generic database values (Table 1). The project note evaluated 244 DBH-based cocoa stems, 27 coffee stems and 104 shade trees for these derived relations, which were structural parameterizations rather than independent destructive calibrations. The D30 cocoa function was applied only within its recorded range (3.29–40.75 cm). Woody root dry biomass was estimated as Br = exp [−1.0587 + 0.8836 ln (Ba)] (Cairns et al. 1997), with Ba and Br in kg.

Consistent with current journal guidance, the source, calibration domain and limitations of each allometric relationship are reported explicitly; uncertainty arising from transferred allometry and root estimation remains a limitation (Cardinael et al. 2025). The musaceae equation fused in here follows a square-root response transformation: its linear predictor is squared before grams are converted to kilograms. Its output is aerial dry biomass only. Field stock was partitioned into above-ground biomass, estimated woody roots and 0–15 cm soil. The measured stock standing reflects the inventory date. The scenario treats old roots and soil as fixed initial pools; root decay and soil changes after felling were not simulated. These pools are existing stock, not new sequestration.

Table 1. Above-ground dry-biomass equations by measured diameter type and functional group; inputs are centimeters for diameter, meters for height and g cm^{-3} for wood density.

Component	Equation / rule	Input and unit
Cacao, D_{30} (beta-GNLS)	$B = 158.097 \times [1 + (35.303-D_{30})/(35.303-23.845)] \times (D_{30}/35.303)^{[35.303/(35.303-23.845)]}$	D_{30} in cm; B in kg dry matter
Cacao, DAP	$B = 0.090940 \times DAP^{2.198400}$	DAP in cm; B in kg
Coffee, DAP	$B = 0.263567 \times DAP^{1.884974}$	DAP in cm; B in kg
Forest/shade, DAP and wood density	$B = 0.221240 \times \rho^{0.976} \times DAP^{2.333520}$	DAP in cm; ρ in g cm^{-3}; B in kg
Musaceae, height	$B = [185.1209 + 881.9471 \times \ln(H)/H^2]^2 / 1000$	H in m; B in kg dry aerial biomass
Roots	Cairns et al. root:shoot relationship	Applied to woody live biomass; not to musaceae

Note. DBH-based equations are derived from local structural parameterizations anchored to Chave et al. (2014), not destructive calibrations. D30 and DBH equations are not interchangeable; roots are estimated only for woody components.

2.4 Preparation-site removal proxies and paired descriptive comparisons

Preparation-site (PPC) records counted trees felled, stem removed and pruning or topping operations (Table 2). These actions were converted to equivalent removed trees using project weights of 1.00 for felling, 0.33/0.75/1.00 for one/two/three stems removed, and 0.35/0.20/0.10 for strong/moderate/light

crown reduction. Prior PCC, baseline tree density data was 650 plants ha^{-1}, on average 205 mature cacao trees were eighter removed or pruned per farm lowering cacao density and tree cover to 444 trees ha^{-1} and from 65% to a 40-45%, respectively. Equivalent trees were multiplied by a farm-specific cocoa above-ground reference stock, or by a documented zonal reference when a local value was unavailable. This intervention-based calculation did not reconstruct a pre-felling census. Complete oxidation of the associated removed above-ground carbon was used only as a conservative scenario assumption; residue retention, harvested-wood storage, burning and fossil-fuel use were not quantified.

Table 2. Tree to tree intervention of Dominican Republic cacao agroforestry systems under the Turrialba method.

Tree to tree intervention under the Turrialba Method	**Conversion factor**	**Average trees removed (cacao** tree **ha-1)**	**Technical considerations following the Turrialba Method**
Tree totally removed	1.0	74	Decayed, old and unproductive tree competing with neighboring cacaos
Tree with one stem removed	0.33	47	Mature tree with stems or branches showing a medium cacao pod load
Tree with two stems removed	0.67	25	Mature tree with stems or branches showing a low cacao pod load.
Tree with three stems removed	0.75	18	Mature tree with no cacao pod load along the remaining stems but providing provisional shade for new cacao seedlings
Tree with heavy crown pruning (60% removed)	0.35	14	Productive tree showing high yield potential recovery after pruning
Tree with moderate crown pruning (40% removed)	0.20	15	Productive tree showing moderate yield potential recovery after pruning
Tree with light crown pruning (20 % removed)	0.10	12	Mature tree showing low yield potential recovery after pruning but providing provisional shade for new cacao seedlings
Total		205	

For the 25 matched farms, inventory-date standing stock and the PPC removal proxy were compared descriptively. The soil-inclusive comparison used the 23 pairs with soil data. PPC work dates were checked against inventory dates for each matched farm. When site preparation preceded the standing-stem inventory, subtracting the PPC proxy from the later stock could not estimate a measured stock change and might double-count removal. The arithmetic stock-minus-PPC value was retained only as a descriptive legacy metric from the technical report, not as a measured post-intervention reserve, treatment effect or carbon balance. The report's relative-reduction index, PPC/(inventory-date above-ground stock + PPC), was likewise not interpreted as an observed proportional loss.

2.5 Diversity, vertical structure and Clark–Evans indices

At plot level we calculated total, cocoa and accompanying-stem abundance; taxonomic richness; Shannon diversity (H′); Simpson diversity (1−D); and Pielou equitability. 'Accompanying' includes all recorded non-cocoa stems, including fruit and shade trees, palms, other woody crops and musaceae; it is not restricted to timber or shade trees. Plot counts were multiplied by ten to report stems per hectare from the 0.1-ha inventory area. Vertical structure was summarized as the percentage of recorded stems below 10 m, from 10 to 20 m, and above 20 m. Nearest-neighbour distances were calculated separately for all stems,

woody stems, cocoa and accompanying stems within each 20 × 50 m inventory plot. Of 1,250 analytical records, 1,242 had usable X/Y coordinates. To account for the rectangular boundary, we simulated 9,999 complete-spatial-randomness patterns uniformly within the same 1,000 m² rectangle, conditional on each plot's observed group size; the pseudorandom seed was 20260924 + group size. The finite-window Clark–Evans index R (Clark and Evans 1954) was the observed mean nearest-neighbour distance divided by the mean of the simulated distances. Two-sided Monte Carlo p values used twice the smaller simulated tail probability with the (1 + b)/(9,999 + 1) correction; $p < 0.05$ and R below or above one denoted nominal aggregation or regularity, respectively.

2.6 Soil chemistry and latent factors

Soil variables included pH, organic matter, total nitrogen and texture fractions. Carbon concentration and soil CO_2e were excluded from the factor analysis to avoid circularly reintroducing the response variable into the explanatory typology. Texture was treated as a compositional constraint and transformed to isometric log-ratio coordinates: $ILR1 = \sqrt{(2/3)}\ \ln[\text{sand}/\sqrt{(\text{clay}\times\text{silt})}]$ and $ILR2 = \sqrt{(1/2)}\ \ln(\text{clay}/\text{silt})$. Variables were standardized before principal-axis factor extraction with varimax rotation. The resulting factor scores were linked to farms by verified identifiers; the two inventory farms without corresponding soil records remained missing for soil factors.

2.7 PCA and exploratory clustering

The primary multivariate analysis used 40 inventory plots. Active variables represented established-cocoa and accompanying-stem counts, richness, Shannon and Simpson diversity, equitability, vertical strata, functional-group carbon stocks and the finite-window R for accompanying stems. Because every inventory plot covered 0.1 ha, counts and per-hectare densities contained the same information; each pair was represented once to avoid duplicate weighting. Cocoa R and soil-factor scores were supplementary variables because they were unavailable for some plots. Positive counts and stocks were transformed with log(1+x), and active variables were standardized before correlation-based PCA. Ward.D2 hierarchical clustering was applied to the first five principal-component scores. Two- and three-cluster partitions were compared by mean silhouette width, with the higher-width partition designated as the primary structural split; the other partition was examined descriptively. A secondary PCA restricted to the 25 plots with both adjusted group-specific R indices assessed sensitivity to inclusion of cocoa spatial structure.

2.8 Fixed 35-year carbon scenario

A single one-hectare renovation design was simulated annually from year 0 to year 35 at a Caciquillo farm (18.834444° N, 69.047222° W). The plot design established 816 grafted cocoa plants ha^{-1} from five clones in alternating double rows at a nominal 3.5 × 3.5 m spacing. Thirty-six boundary timber and fruit shade trees were added, six individuals each of *Cordia alliodora*, *Simarouba glauca*, *Cedrela odorata*, *Citrus aurantium*, *Persea americana* and *Artocarpus altilis*. Only their biomass-carbon trajectories enter the present analysis; simulated bean and fruit yields are outside its scope.

We used a deterministic empirical age–biomass projection model for the 35-year renewal scenario. Age–biomass curves were fitted to the cocoa biomass measurements reported by Leiva-Rojas and Ramírez-Pisco (2021) for trees aged 4–30 years across three tropical life zones. We selected the tropical moist forest (bh-T) curve as the closest ecological analogue for the Dominican scenario and extended its fitted trajectory by

five years, from age 30 to 35. Cocoa biomass at the reference density of 1,111 plants ha^{-1} was adjusted to 800 plants ha^{-1} using a density exponent of 0.65 and a clonal-design factor of 1.05. Boundary-tree biomass followed species-specific asymptotic growth curves with root and permanence factors. Dry biomass of both cocoa and boundary trees was converted to carbon using a fraction of 0.47 and then to CO_2e using 44/12.

An ancillary eco-physiological analysis used daily climate data from NASA POWER for Caciquillo covering 1 January 2010 to 31 December 2024 (NASA Langley Research Center, n.d.). It described canopy development, intercepted radiation, net primary production, root depth, and water and temperature stress. These diagnostics provided environmental context; the 35-year carbon-stock trajectory was calculated from the bh-T cocoa age–biomass curve described above and species-specific boundary-tree growth curves. Stocks of new cocoa and boundary trees were reported separately from the existing stand and compared with estimated PPC removal as a hypothetical replacement benchmark. Illustrative total-stock curves held measured soil carbon (0–15 cm) and old-root stocks constant and included a modelled remainder of the old stand. Because the standing stock inventory followed felling, that remainder was an assumption rather than an observed post-felling stock. The scenario did not account for decomposition, harvested wood, operational emissions, or tree mortality and replacement.

2.9 Statistical reporting

Unless otherwise indicated, summary values are reported as mean ± standard error (SE), observed range and sample size (n). Principal component analysis, Ward.D2 clustering, silhouette calculations and the 35-year carbon-stock scenario were implemented in R (R Core Team 2026).

3 Results

3.1 Consolidated coverage and biomass stocks

The final database included 40 inventories with 1,250 analytical individuals. Cocoa accounted for 873 stems and accompanying taxa for 277 stems in the quality-controlled analytical file. Musaceae occurred in 18 inventory farms and were included as aerial non-woody biomass and as diversity records. Record availability by data source is summarized (Table S1). Carbon stocks were highly heterogeneous among cocoa farms. Above-ground biomass ranged from 6.60 to 894.56 Mg CO_2e ha^{-1}, while total system stock ranged from 96.02 to 1,112.53 Mg CO_2e ha^{-1} among farms with soil data (Figure 2). The broad range reflects differences in cacao density, retained overstorey, fruit trees, palms, plot history and the presence or absence of large stems, rather than a single uniform plantation architecture.

Table 3. Mean, standard error and observed range of above-ground, root, live and 0–15 cm soil carbon-equivalent stocks in the Dominican Republic cocoa agroforestry inventory plots (Mg CO_2e ha^{-1}).

Pool	n farms	Mean ± SE (Mg CO_2e ha^{-1})	Observed range
Above-ground live biomass	40	169.33 ± 30.89	6.60–894.56
Roots	40	23.30 ± 3.35	1.30–96.55
Live biomass (above-ground + roots)	40	192.63 ± 34.21	7.90–990.43
Soil carbon equivalent	38	112.57 ± 2.55	73.16–132.62
System (live + soil)	38	306.60 ± 36.45	96.02–1112.53

Note. CO_2e values are carbon stocks expressed using the project conversion factors; soil is reported only where measured and linked.

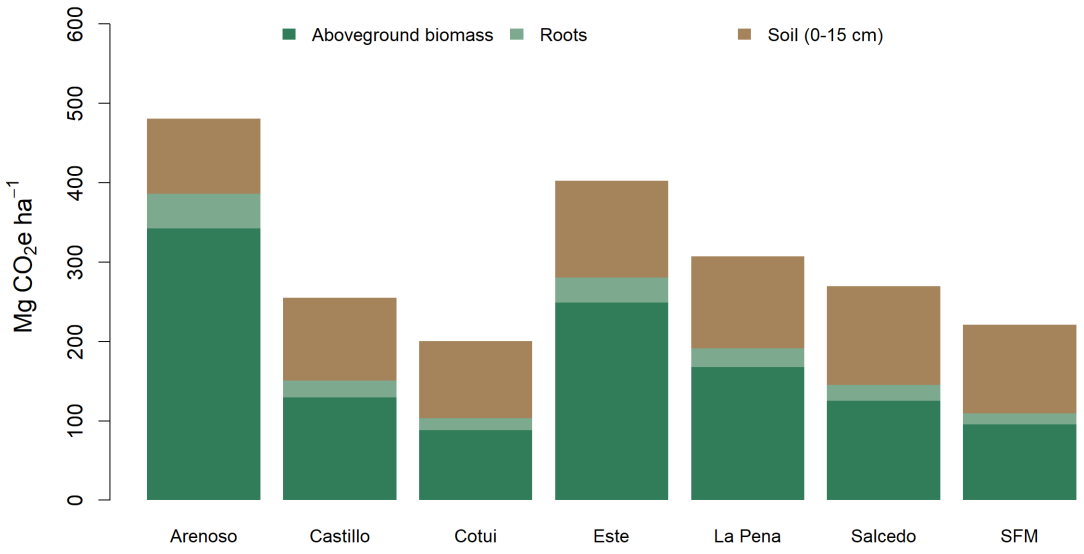


Figure. 2. Above-ground, root, 0–15 cm soil and total system carbon-equivalent stocks by sampled zone in the Dominican Republic cocoa agroforestry systems; sample size varies by measured pool.

3.2 Preparation-site removal proxies and paired descriptive comparisons

The corrected PPC file contained 26 valid farm records, 25 of which could be paired to an inventory. Across those pairs, inventory-date live stock averaged 154.05 ± 34.22 Mg CO_2e ha^{-1} and the PPC above-ground removal proxy averaged 93.72 ± 11.44 Mg CO_2e ha^{-1}. The legacy arithmetic difference averaged 60.34 ± 35.68 Mg CO_2e ha^{-1} and was negative in 12 pairs; it is not a measured carbon loss or residual stock (Table 4). For the 23 pairs with soil estimates, inventory-date system stock averaged 259.50 ± 37.40 Mg CO_2e ha^{-1} (Figure 3). These quantities are retained as descriptive comparisons because intervention and inventory timing do not define a before–after design.

Table 4. Inventory-date stock, estimated preparation-site removal proxy and legacy arithmetic differences for 25 matched Dominican agroforestry cocoa plots (23 with 0–15 cm soil data).

Metric	n	Mean ± SE	Range
Inventory-date live stock (Mg CO_2e ha^{-1})	25	154.05 ± 34.22	7.90–872.26
PPC removal (Mg CO_2e ha^{-1})	25	93.72 ± 11.44	36.83–258.73
Legacy arithmetic difference (live stock − PPC) (Mg CO_2e ha^{-1})	25	60.34 ± 35.68	−75.98–818.38
Report reduction index (%)	25	49.6 ± 4.2	6.5–89.9
Inventory-date system stock (Mg CO_2e ha^{-1})	23	259.50 ± 37.40	96.02–972.33
Legacy arithmetic difference (system stock − PPC) (Mg CO_2e ha^{-1})	23	165.85 ± 38.78	37.40–918.46

Note. PPC is an estimated above-ground potential removal. Stock-minus-PPC values are not direct before–after measurements or post-intervention reserves. The reported relative-reduction index is PPC/(inventory-date above-ground stock + PPC), not an observed proportional loss.

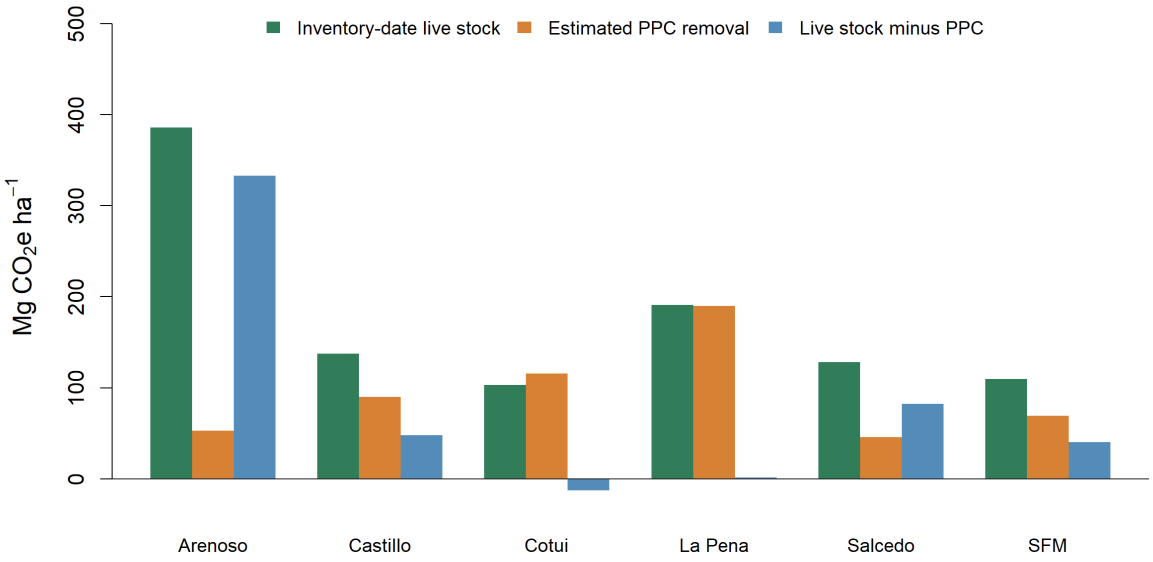


Figure. 3. Inventory-date live carbon-equivalent stock and the estimated above-ground PPC removal proxy by zone for the 25 matched inventory–intervention plots in Dominican Republic cocoa agroforestry systems.

3.3 Diversity, density, vertical structure and spatial arrangement

Across 40 analytical plots, mean total density was 612.5 stems ha⁻¹, including 218.3 recorded cocoa stems ha⁻¹ and 94.3 accompanying stems ha⁻¹. Thirteen plots had no recorded cocoa, which lowers the pooled mean; among the 27 plots with at least one cocoa stem, the calculated mean was 423.3 cocoa stems ha⁻¹. In the 16 plots in clusters 1 and 2, recorded felling preceded the June 2026 inventory, and replanted cocoa seedlings were excluded (Table 5). Mean richness was 4.85 taxa per inventory, Shannon diversity was 0.929 and Simpson diversity (1−D) was 0.465. The vertical profile was dominated by stems below 10 m (65.6%), followed by the 10–20 m layer (28.6%) and a smaller >20 m layer (5.8%). These values describe a structurally heterogeneous cocoa agroforestry matrix rather than a regular, single-species orchard.

Table 5. Stem density, diversity, height strata and separate cocoa and non-cocoa accompanying-stem Clark–Evans indices in the 40 Dominican Republic cacao inventory plots.

Variable	n	Mean ± SE
Total density (stems ha⁻¹)	40	612.5 ± 34.9
Cacao density (stems ha⁻¹)	40	418.3 ± 31.4
Companion density (stems ha⁻¹)	40	94.3 ± 10.4
Taxonomic richness	40	4.85 ± 0.27
Shannon H′, total	40	0.929 ± 0.061
Simpson 1−D, total	40	0.465 ± 0.033
Pielou equitability, total	40	0.622 ± 0.041
Stems <10 m (%)	40	65.6 ± 5.6
Stems 10–20 m (%)	40	28.6 ± 4.9
Stems >20 m (%)	40	5.8 ± 1.8
Cocoa Clark–Evans R	25	1.087 ± 0.045
Companion Clark–Evans R	40	0.886 ± 0.039

Note. R is calibrated to the 20 × 50 m plot boundary using 9,999 fixed-count CSR simulations per group size. Cocoa R is estimable for 25 plots (mean 1.087 ± 0.045 SE) and accompanying-stem R for all 40 (0.886 ± 0.039 SE); the other 15 plots had fewer than two valid cocoa stems. Categories use nominal two-sided Monte Carlo $p < 0.05$, not fixed R cut-offs. Coincident coordinates contribute zero distance; results for affected plots depend on the tie convention.

The group-specific Clark–Evans results were complementary. With finite-window calibration and nominal two-sided Monte Carlo tests, the all-stem patterns comprised six aggregated plots, 18 without a detected departure from CSR and 16 regular plots. Mean adjusted R was 1.087 ± 0.045 SE for cocoa in 25 plots and 0.886 ± 0.039 SE for accompanying stems in all 40. The corresponding counts were one aggregated, 15 without a detected departure and nine regular cocoa patterns; for accompanying stems, five were aggregated, with six approximately random and 3 regular. and 36 showed no detected departure. This contrast supports the use of separate cacao and companion indices: a managed cacao component can show regular spacing while retained or naturally regenerated companions remain clustered.

3.4 Soil latent factors, PCA and farm clusters

The soil factor analysis reduced pH, organic matter, nitrogen and texture coordinates to two interpretable latent dimensions. Factor 1 was dominated by organic matter (loading 0.94), nitrogen (0.91) and pH (0.66), whereas Factor 2 was primarily associated with the clay–silt texture contrast (ILR2 loading −0.58). Texture ILR1 contributed weakly to both factors. Carbon concentration and soil CO_2e were not used to define these factors. The silhouette-preferred two-cluster partition separated 16 plots with few established cocoa stems from 24 cocoa-rich plots (mean silhouette 0.380). The descriptive three-cluster split (silhouette 0.361) divided those 16 low-cocoa plots into clusters of nine and seven while leaving the 24-plot group intact. Clusters 1 and 2 contained only three and one established cocoa stems, equivalent to means of 3.3 and 1.4 stems ha^{-1}; cluster 3 contained 869 stems (362.1 stems ha^{-1}). Their low densities describe established cocoa remaining during renovation, not original orchard or new-planting density. The two low-cocoa subgroups differed in mean live-stock (222.61 versus 104.04 Mg CO_2e ha^{-1}) and companion diversity (mean Shannon H′ 0.89 versus 1.52); the cocoa-rich group averaged 207.23 Mg CO_2e ha^{-1}. The full descriptive profiles and ordination are in Table S3 and Fig. S2. In the 25-plot sensitivity PCA including both adjusted group-specific R indices, the two-cluster solution isolated one plot and was not treated as an independent classification.

3.5 Fixed 35-year renovation scenario

Using a carbon fraction of 0.47 for both cocoa and boundary trees, the fixed new-cohort trajectory reached 70.48 Mg CO_2e ha^{-1} at year 20, 74.68 Mg CO_2e ha^{-1} at year 30 and 73.94 Mg CO_2e ha^{-1} at year 35 (Table 6; Figure 4). At year 35, cocoa and boundary trees contributed 51.45 and 22.49 Mg CO_2e ha^{-1}, respectively. These values are projected standing stocks of the new cohort, not annual sequestration rates. Relative to the mean PPC removal proxy of 93.72 Mg CO_2e ha^{-1} in the 25 matched farms, the projected year-35 stock was 19.78 Mg CO_2e ha^{-1} lower. This difference is a scenario benchmark, not a measured net loss, validated payback time or greenhouse-gas balance. Illustrative high- and low-stock farms were compared under one or two intervention phases (Online Resource 1, Fig. S3). The second phase assumes an additional removal equal to the first in year 2. These curves show how the assumed timing and amount of old-stock removal affect projected total stock; they do not represent treatment effects measured in the field. After two removal phases, projected total stock in neither example returns to its hypothetical initial level within 35 years.

Table 6. Projected new cocoa and boundary-tree carbon-equivalent stocks at years 20, 30 and 35 for the fixed one-hectare in Caciquillo model farm following the Turrialba renovation design.

Scenario output	Year 20	Year 30	Year 35
New total stock (Mg CO_2e ha^{-1})	70.48	74.68	73.94
New cocoa stock (Mg CO_2e ha^{-1})	53.06	53.35	51.45
Boundary-tree stock (Mg CO_2e ha^{-1})	17.42	21.33	22.49

Note. The five-clone, 800-cocoa-plant and 36-boundary-tree design is a transferred, fixed scenario. Values are accumulated new-cohort stocks; old surviving biomass, roots and soil are excluded from this table.

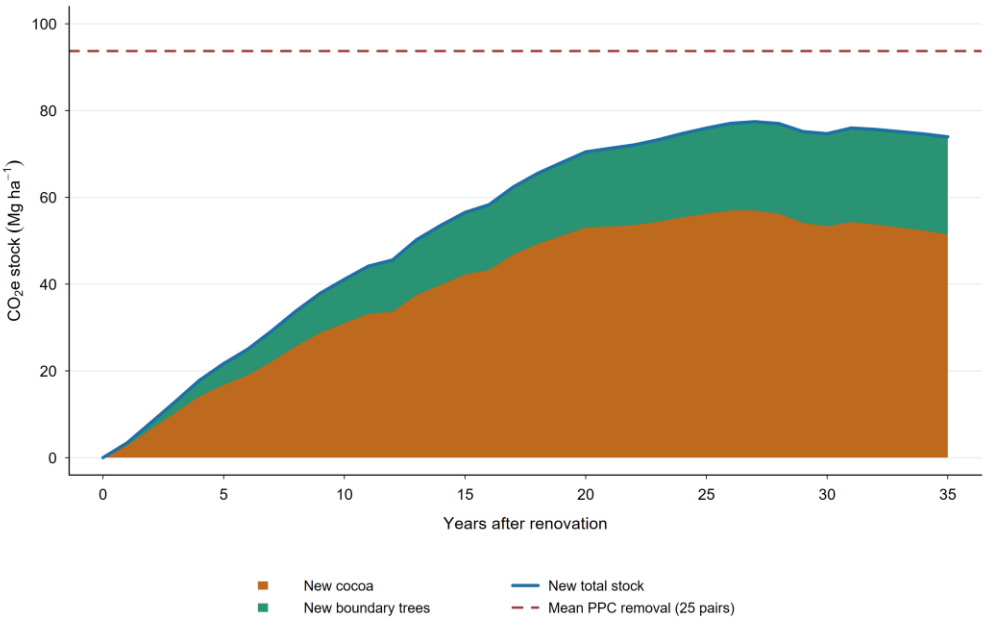


Figure. 4. Fixed 35-year new-cohort carbon-equivalent stock trajectory for 800 grafted cocoa plants and 36 boundary trees per hectare at Caciquillo model agroforestry farm in the Dominican Republic.

4 Discussion

4.1 Heterogeneous stocks reflect agroforestry mosaics

Standing above-ground biomass varied widely among the 40 plots (6.60–894.56 Mg CO_2e ha^{-1}), consistent with heterogeneous retained-tree size and composition. The mean above-ground value of 169.33 Mg CO_2e ha^{-1} corresponds to approximately 46.18 Mg C ha^{-1}. Suárez et al. (2026b) reported 14.5 Mg C ha^{-1} for above-ground biomass and necromass in Colombian Amazon cocoa agroforestry, but the pool definitions, stand ages and sampling frames differ. In Central America, cocoa the total carbon stocked in cocoa-based agroforestry systems in Central America is **1**17±47 Mg C ha^{-1}, with 51 Mg C ha^{-1} in the soil and 49 Mg C ha^{-1} in aboveground biomass (cocoa and canopy trees). The comparison is therefore contextual rather than evidence that one region stores more carbon than another. More generally, shade-tree abundance and size can dominate woody carbon in cocoa agroforestry, but high carbon stock does not by itself establish

a production advantage or a mitigation benefit (Somarriba et al. 2013; Notaro et al. 2021; Mora Garces et al. 2026).

4.2 Why separate cacao and companion Clark–Evans indices?

Because spatial arrangement can influence light competition and management, we describe cocoa and companion stems separately using density, diversity, height strata and nearest-neighbour structure. We then examine how these descriptors co-vary with biomass stocks and use multivariate ordination as an exploratory description of plot structure. The contribution of this study is to place standing stocks, intervention records and a clearly separated renovation-growth scenario within the same dated project framework, while making their different evidential status explicit. The finite-window Clark–Evans analysis confirms that cocoa and accompanying stems should be mapped separately rather than collapsed into a single structural descriptor. Its adjusted means are closer to or below one than the uncorrected values, and the nominal plot-level CSR categories change appreciably. For some plots, identical recorded X/Y locations also change categories according to whether those locations are treated as separate stems or unique points. Accordingly, the present spatial findings describe the recorded stem locations; they do not establish a planting design or a productivity mechanism. Notaro et al. (2021) showed that companion type, height and distance can be associated with cocoa productivity, but plot-level harvest data were unavailable here. Moreover, the PCA and Ward analyses compress correlated structural indicators, but the strongest split is between the 16 plots with very few established cocoa stems and the 24 cocoa-rich plots. Silhouette width slightly favours this two-group split. We present the three-group result only to expose variation within the low-cocoa set: one subgroup had more retained live carbon, whereas the other had higher companion diversity. Because those plots were inventoried after documented 2025 felling and replanted seedlings were excluded and renovation stage is confounded with the typology. Neither partition is a validated ecological classification or a basis for cluster-specific management rules.

4.5 Limitations and next steps

The principal limitation is temporal: The PPC calculation is an intervention-based proxy using project weights and a complete-oxidation assumption; its uncertainty has not been independently validated. Biomass estimates rely on transferred or locally parameterised allometry without destructive validation, root biomass is modelled, and the soil pool is shallow and partly derived from pedotransfer information. The 35-year trajectory uses a bh-T age–biomass curve fitted to a published pseudocronosequence of cocoa trees aged 4–30 years (Abou-Rajab et al., 2016. Leiva-Rojas and Ramírez-Pisco 2021). Extending the curve from age 30 to 35 adds five years beyond the observed age range, and the resulting trajectory has not been validated for the Dominican replacement cohort.

Across project´s target farms the Turrialba scenario represents progressive establishment of 800 grafted cocoa plants ha^{-1} in double rows together with boundary trees, while part of the old canopy remains temporarily. The model is treated here as a fixed planning benchmark, not as a validated forecast or as a comparison of the agronomic or economic performance of alternative renovation methods. Field calibration and validation remain necessary before using simulated growth to infer carbon recovery in Dominican farms (Tosto et al. 2023; Romero Vergel et al. 2022). At year 35, projected new-cohort stock (73.94 Mg CO_2e ha^{-1}) was lower than the mean PPC removal proxy (93.72 Mg CO_2e ha^{-1}). This 19.78 Mg CO_2e ha^{-1} difference should be read only as a planning benchmark under the specified assumptions. Lower-removal

interventions, greater retention of old canopy, improved survival or a different planting design could change the trajectory, but each option requires an explicit scenario and field verification. The comparison should not be converted into a claim of net greenhouse-gas emissions without measured residue fate, repeated stocks and production-system emissions (Cornelius et al. 2025).

The mean 0–15 cm soil estimate (112.57 Mg CO_2e ha^{-1} in 38 linked plots) should be interpreted as an existing project stock estimate, not as carbon sequestered by renovation. Its comparability is limited because organic carbon was derived from organic matter, bulk density was estimated with a pedotransfer function, the available files do not fully document sampling replication or coarse fragments, and the sampled depth is shallower than the 0–30 cm profile recommended by Cardinael et al. (2025) for SOC and bulk density. Those guidelines also call for measured bulk density and depth-specific reporting. Thus our 0–15 cm estimate describes the sampled project layer only; it cannot establish a renovation-driven change in soil carbon or stand in for a 0–30 cm stock. In addition, estimated oxidation of removed biomass is a scenario assumption rather than a measured emission, whereas biomass and soil values are stocks at a defined observation time. A complete climate assessment would additionally require residue fate, harvested-wood pools, management emissions, land-use history and repeated carbon measurements (Cornelius et al. 2025; Mora Garces et al. 2026; Santos et al., 2026). For the Dominican Republic and comparable Caribbean cocoa landscapes, the immediate implication is to account for carbon before approving pruning or felling, while protecting productive canopy and soil where feasible. Regional transfer should use harmonized pool boundaries and soil depths. The study provides an operational baseline and a transparent question for subsequent monitoring—when, and under which renovation intensity, does measured new stock replace the stock removed?—rather than a site mitigation factor.

5 Conclusions

Cocoa agroforestry plots in the Dominican project frame contained substantial but highly variable standing biomass. The inventory and preparation-site records are informative for renovation planning, but their timing does not constitute a before–after carbon design. Consequently, intervention-based removal proxies, inventory-date stocks and simulated replacement growth must remain analytically separate. Under the fixed Turrialba design, projected new cocoa and boundary-tree stock at year 35 remained below the mean intervention-based removal proxy. This comparison identifies a carbon accounting question for renovation rather than a verified payback period. A submission-ready analysis should prioritize reproducible allometric inputs, complete soil-sampling metadata, harmonized carbon-fraction reporting, validation of the source inventory records and field validation of the replacement cohort. The finite-window spatial reanalysis strengthens the description of recorded stem locations, while repeated permanent-plot measurements linking residual trees, new cocoa, soil and production would allow future work to quantify actual stock change and test whether lower-removal renovation pathways improve carbon retention.

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Competing interests

The authors declare no competing interests. This statement should be confirmed by all co-authors.

Author contributions

Argenis A. Mora Garcés: conceptualization, field-data curation, methodology, analysis and drafting. Luis Orozco Aguilar: conceptualization, project coordination, field programme and review. The remaining authors reviewed and approved the final version of the manuscript.

Data availability

The processed farm-level database and analysis code are available from the corresponding author on reasonable request, subject to producer confidentiality and project data-governance agreements. Individual producer identifiers should not be deposited in an open repository without permission.

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