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# Silvicultural management of Brazil nut trees for wood and fruit production in a commercial plantation in the Amazon

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***Keywords*— Bertholletia excelsa; volume equation; Brazil nut production; multiple-use management.**

***Abstract*— *Background: This study integrated rigorous stem volume measurements and reproductive monitoring to evaluate the management of commercial Brazil nut (Bertholletia excelsa Bonpl.) plantations in the Amazon. Wood productivity was assessed in 110 trees aged 9–23.5 years by fitting 23 equations for total volume over bark. Fruit production comprised six harvests (2013, 2016, 2020, 2024, 2025, and 2026), five clones, and individually identified trees. Materials and Methods: A total of 110 cubed trees aged 9–23.5 years were analyzed, and 23 equations for total volume over bark were fitted. Fruit production was evaluated over six harvests by clone and tree using descriptive statistics and a linear mixed-effects model with harvest as a fixed effect and clone and tree nested within clone as random effects. Pearson and Spearman correlations were used to explore associations with annual precipitation. Results: The double-entry Weibull model based on diameter at breast height (DBH) and total height showed the best volumetric performance (RMSE = 0.1006 m³; adjusted $R^2$ = 0.9623; CV-RMSE = 0.1078 m³). Estimated mean volumes ranged from 0.254 to 0.640 m³ tree$^{-1}$ across age strata. For reproductive production, clone m_pedro yielded 3,440 fruits, and tree m_pedro527 yielded 757 fruits over six harvests. Variance in transformed production was partitioned into 21.7% among clones, 26.7% among trees within clones, and 51.6% residual variance. Total production was not significantly associated with annual precipitation in the preceding year ($r = -0.03$; $p = 0.900$) or two years earlier ($r = 0.24$; $p = 0.389$). The results support inventories based on DBH and height, simultaneous selection at the clone and tree levels, and continued monitoring. Conclusion: The double-entry Weibull equation is recommended for local inventories within the sampled range. Selection of reproductive material should combine mean clone performance, individual superiority, and stability across multiple harvests. Future integration of growth and fruiting measurements on the same trees is required to define multiple-use management regimes.**

# I. INTRODUCTION

The Brazil nut tree is an Amazonian species of major ecological and socioeconomic importance. It provides a high-value non-timber forest product and, in legally established plantations operated under the applicable permits, high-quality wood. Commercial cultivation increases the need to reconcile growth, stem form, crown development, and reproductive production. Plantation studies show that the species responds to light availability and that spacing affects growth and morphometric attributes (Scoles, Gribel, and Klein 2021; Oliveira et al. 2021).

Recent syntheses have emphasized that the species' ecophysiological plasticity enables its use in pure plantations, agroforestry systems, enrichment planting, and restoration, and that spacing, fertilization, and thinning can increase growth, biomass, and fruit production (de Souza et al. 2023; Gonçalves, Costa, and Lima 2023; Lima et al. 2023). In Central Amazonian plantations, site quality follows polymorphic patterns and varies primarily with sand content and elevation, followed by soil chemical attributes, indicating that environmental stratification should be incorporated into inventory planning and management (Souza et al. 2023).

Planning for multiple-use silvicultural management requires information at two scales. The first is dendrometric: local equations convert DBH and height into volume, support forest inventories, and allow comparisons of growing stock under different ages and stand densities. The second is reproductive: fruit production varies among years and individuals; therefore, decisions based on a single harvest may select unstable material. Studies in natural populations confirm strong individual heterogeneity and the need for repeated measurements over several years (Wadt, Kainer, and Gomes-Silva 2005; Azevedo et al. 2020).

Precipitation is one of the environmental factors that may affect fruiting over time scales preceding harvest, but the response depends on the climatic window and local conditions; extreme events such as El Niño may also reduce production (Rocha et al. 2021). Simple annual correlations should therefore be interpreted as exploratory analyses rather than evidence of a causal mechanism.

This study aimed to integrate results from the management of Brazil nut trees for wood and fruit production in order to: (i) evaluate equations for total volume over bark; (ii) summarize fruit productivity by clone and tree; (iii) examine the hierarchical partitioning of reproductive variability and its exploratory association with precipitation; and (iv) derive implications for the silvicultural management of commercial Brazil nut plantations.

# II. MATERIAL AND METHODS

### *Study area*

The study was conducted on land owned by Agropecuária Aruanã Ltda. in the municipality of Itacoatiara, Amazonas, Brazil (Figure 1), in a tropical humid climate and on soils predominantly classified as dystrophic Yellow Oxisols. The company's commercial plantations occupy areas previously altered by deforestation and pasture use and include stands intended for wood production and clonal stands managed for fruit production.

### *Synthesis design and datasets*

Two independent analytical datasets were integrated. The dendrometric dataset comprised 1,170 sectional stem measurements obtained from 110 independent trees. The reproductive dataset comprised fruit counts by tree, clone, and harvest. Integration was performed at the results level because no common identifier was available to match volume and fruit production for the same trees, and plantations intended for fruit and wood production are managed under different regimes.

### *Total volume over bark*

Individual-tree volume was obtained by rigorous stem cubing. Intermediate sections were calculated using Smalian's method and supplemented with a cylindrical basal section and a conical top section extending to total height. Nine single-entry models (DBH), nine double-entry models (DBH and height), and five age-dependent models were evaluated, totaling 23 equations (Table 1). Parameters were estimated by nonlinear least squares. Models were compared using RMSE, MAE, bias, standard error of estimate, adjusted $R^2$, AIC, BIC, and ten-fold cross-validation. Cross-validation was used to assess predictive performance outside the fitting partitions (Stone 1974), whereas AIC and BIC were used to balance goodness of fit and model complexity (Burnham and Anderson 2002).

The main equation families evaluated, their general forms, and references are presented in Table 1.

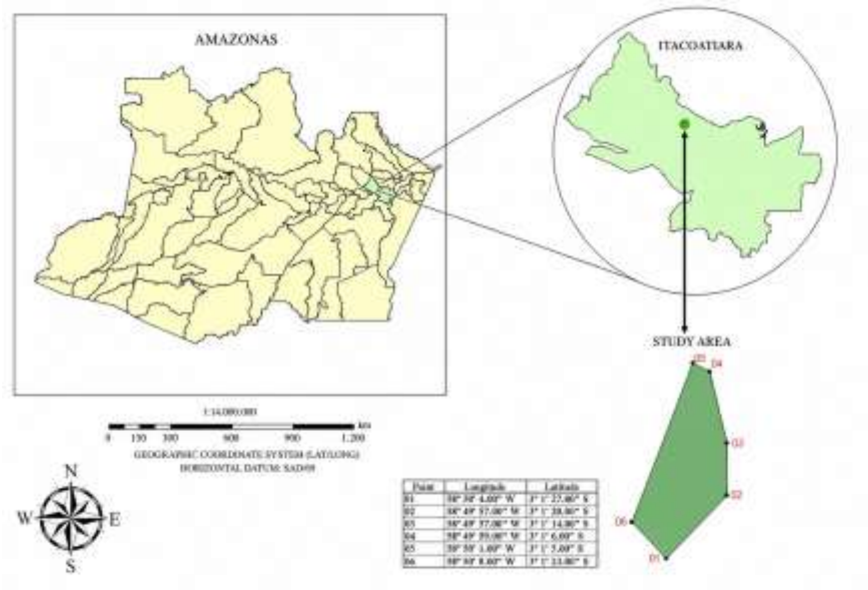


*Fig.1. Location of the study area at Agropecuária Aruanã in Itacoatiara, Amazonas, Brazil.*

Source: Adapted by the authors from Agropecuária Aruanã Ltda.

*Table 1. Main families of volume models evaluated.*

| Group | Models | General form | Reference |
|---|---|---|---|
| Single-entry | Logistic; Gompertz; Bertalanffy–Richards; Weibull | v = f(d), in sigmoid forms | Rolim and Piotto (2024) |
| Single-entry | Schumacher; Husch; Brenac | $v = b_0 \exp(b_1/d)$; $v = b_0 d^{b_1}$; $v = b_0 d^{b_1} \exp(b_2/d)$ | Loetsch et al. (1973) |
| Single-entry | Dissescu–Meyer; Hohenadl–Krenn | $v = b_1 d + b_2 d^2$; $v = b_0 + b_1 d + b_2 d^2$ | Loetsch et al. (1973) |
| Double-entry | Arithmetic and power Spurr | $v = b_0 + b_1 d^2 h$; $v = b_0 (d^2 h)^{b_1}$ | Spurr (1952) |
| Double-entry | Schumacher–Hall | $v = b_0 d^{b_1} h^{b_2}$ | Loetsch et al. (1973) |
| Double-entry | Honer; Ogaya; Näslund; Takata; Meyer | Classical forms using d and h | Loetsch et al. (1973) |
| Double-entry | Weibull with height | $v = b_0[1 - \exp\{-(d/b_1)^{b_2}\}] h^{b_3}$ | Adapted Weibull; Rolim and Piotto (2024) |
| Age-dependent | Power; inverse exponential; combined variable; Logistic; Gompertz | Extensions using d, h, and age (I) | Forms adapted in this study |

Note: v = total volume over bark ($m^3$); d = DBH over bark (cm); h = total height (m); I = age (years); $b_0, \ldots, b_k$ = model parameters.

Volume per hectare was estimated separately for each age stratum by expanding mean individual-tree volume: $\hat{V}_{ha,i} = N_i \times \bar{v}_i$, where $N_i$ is stand density (trees per hectare) and $\bar{v}_i$ is mean volume predicted by the Weibull equation for stratum i. The 95% confidence limits per hectare were obtained by multiplying the 95% confidence limits of mean individual-tree volume by $N_i$. ANCOVA was not used because stand density is an expansion factor rather than an individual-tree covariate. The number of cubed trees contributed to the precision of the mean for each stratum but was not used as a population weight; calculation of an overall weighted mean would require knowledge of the area represented by each stratum.

### *Fruit production and hierarchical variability*

Fruit production was assessed for the 2013, 2016, 2020, 2024, 2025, and 2026 harvests. Totals and means were calculated by clone, tree, and harvest. To separate sources of variation, the following linear mixed-effects model was fitted by restricted maximum likelihood: $y_{sca} = \beta_0 + \beta_s + u_c + v_{a(c)} + \varepsilon_{sca}$, where:

$y_{sca} = \log[1 + n_{sca}]$ is the transformed production of tree a belonging to clone c in harvest s;

$\beta_0$ is the intercept;

$\beta_s$ is the fixed effect of harvest (2013 as the reference);

$u_c$ is the random clone intercept;

$v_{a(c)}$ is the random intercept of tree nested within clone; and

$\varepsilon_{sca}$ is the residual error.

The terms $u_c \sim N(0, \sigma^2 clone)$, $v_{a(c)} \sim N(0, \sigma^2 tree)$, and $\varepsilon_{sca} \sim N(0, \sigma^2)$ were assumed to be mutually independent.

In R notation, the model was fitted as log1p(n_fruits) ~ harvest + (1 | clone_id/tree_id). The transformation retained zero values and reduced skewness.

### *Precipitation*

Annual precipitation totals were obtained from the INMET-Itacoatiara weather station (A121) and related to production in harvests one and two years later. Pearson and Spearman correlations were calculated. The small number of coincident years and replication of the same precipitation value among clones limited inference; these tests were therefore interpreted as exploratory.

## III. RESULTS

### *Management for wood production*

Descriptive statistics for the 110 cubed trees are presented in Table 2.

*Table 2. Descriptive statistics for the 110 cubed trees.*

| Variable | Minimum | Mean | Median | Maximum | Standard deviation |
|---|---|---|---|---|---|
| Age (years) | 9.000 | 17.064 | 21.000 | 23.500 | 5.572 |
| DBH (cm) | 8.600 | 27.635 | 25.700 | 53.000 | 10.349 |
| Total height (m) | 11.100 | 20.466 | 20.150 | 29.000 | 4.484 |
| Commercial height (m) | 4.600 | 13.232 | 13.400 | 21.500 | 3.304 |
| Total volume (m³) | 0.031 | 0.683 | 0.499 | 2.287 | 0.528 |

### *Performance of volume equations*

All 23 models tested for volume estimation converged. The double-entry Weibull equation,

$$v = b_0\{1 - exp[-(d/b_1)^{b_2}]\}h^{b_3},$$

showed the best fitting and cross-validation performance: RMSE = 0.1006 m³, MAE = 0.0616 m³, adjusted $R^2$ = 0.9623, relative standard error = 15.00%, and CV-RMSE = 0.1078 m³. Mean bias was 0.13%, indicating little systematic trend within the sample.

Table 3 presents the best-performing equation in each model group according to ten-fold cross-validation.

*Table 3. Best-performing equation in each group according to ten-fold cross-validation.*

| Group | Model | RMSE | MAE | Bias (%) | Syx (%) | Adjusted R² | CV-RMSE |
|---|---|---|---|---|---|---|---|
| Single-entry | Weibull | 0.1076 | 0.0672 | 0.1033 | 15.98 | 0.9572 | 0.1128 |
| Double-entry | Weibull | 0.1006 | 0.0616 | 0.1315 | 15.00 | 0.9623 | 0.1078 |
| Age-dependent | Gompertz-age | 0.1166 | 0.0865 | −1.4730 | 17.48 | 0.9488 | 0.1164 |

Note: RMSE = root mean square error; MAE = mean absolute error; Syx = standard error of estimate; CV-RMSE = cross-validated root mean square error.

Figure 2 compares observed volumes with the fitted curves for the three best-performing models in each group.

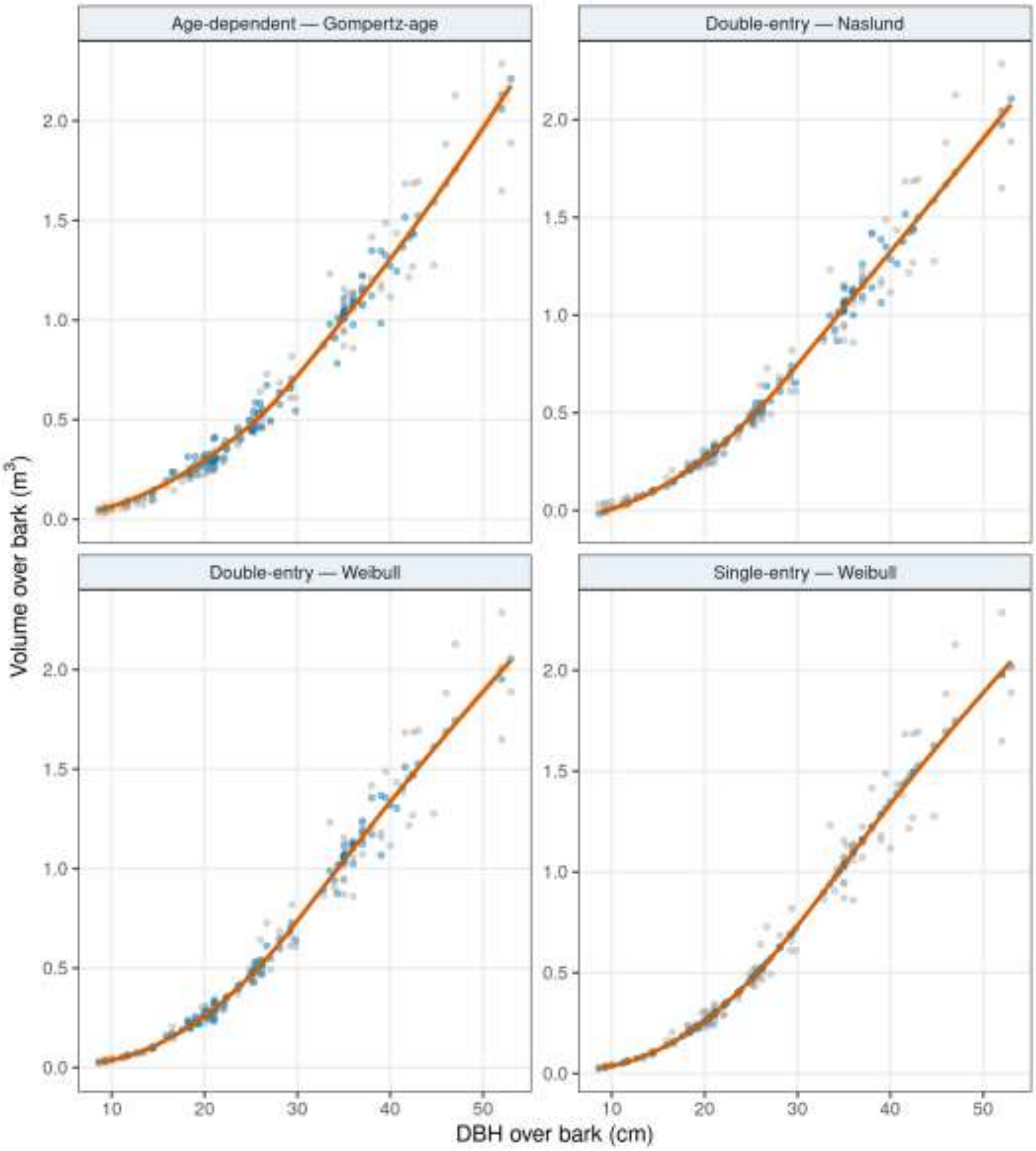


*Fig.2. Observed volume and fitted curves for the three best-performing models.*

*Source: Authors' data.*

Estimated mean individual-tree volume ranged from 0.254 m³ tree⁻¹ at age 9 to 0.640 m³ tree⁻¹ at age 23.5. At the recorded stand densities, estimated growing stock ranged from 256.5 to 605.0 m³ ha⁻¹ in the 9–15-year strata and was 477.4 m³ ha⁻¹ in the 23.5-year stratum. The corresponding mean annual increments ranged from 20.3 to 40.3 m³ ha⁻¹ year⁻¹. These estimates are stratum-level expansions and do not represent a controlled chronosequence.

Volume estimates by age stratum and stand density are presented in Table 4.

### *Fruit production by clone and tree*

Clone m_pedro had the highest cumulative production, yielding 3,440 fruits over six harvests, followed by aruana (2,599), santa_fe (1,899), 606 (1,157), and 609 (646). Ranking by cumulative production was identical to ranking by mean production per tree per harvest, reducing—but not eliminating—the concern that the ranking merely reflected differences in the number of monitored trees.

Cumulative production and mean production per tree per harvest for each clone are presented in Table 5.

*Table 4. Estimated volume by age stratum and stand density.*

| Age (years) | n | N (trees ha⁻¹) | $\bar{v}$ (m³ tree⁻¹) | Lower 95% CI | Upper 95% CI | $\hat{V}$ (m³ ha⁻¹; 95% CI) | MAI of $\hat{V}$ (m³ ha⁻¹ year⁻¹) |
|---|---|---|---|---|---|---|---|
| 9.0 | 24 | 1,010 | 0.254 | 0.178 | 0.331 | 256.5 (179.8–334.3) | 28.5 |
| 10.0 | 10 | 1,010 | 0.302 | 0.282 | 0.322 | 305.0 (284.8–325.2) | 30.5 |
| 15.0 | 10 | 1,010 | 0.599 | 0.495 | 0.702 | 605.0 (500.0–709.0) | 40.3 |
| 23.5 | 10 | 746 | 0.640 | 0.305 | 0.975 | 477.4 (227.5–727.4) | 20.3 |

Note: n = number of cubed trees; N = stand density; $\bar{v}$ = mean predicted individual-tree volume; $\hat{V} = N \times \bar{v}$; MAI = mean annual increment. The 95% CI for $\hat{V}$ was obtained by expanding the 95% confidence limits of $\bar{v}$.

*Table 5. Cumulative fruit production by clone.*

| Rank | Clone | Total fruits | Harvests | Trees | Mean tree⁻¹ harvest⁻¹ |
|---|---|---|---|---|---|
| 1 | m_pedro | 3,440 | 6 | 13 | 57.6 |
| 2 | aruana | 2,599 | 6 | 10 | 46.0 |
| 3 | santa_fe | 1,899 | 5 | 11 | 39.4 |
| 4 | 606 | 1,157 | 6 | 12 | 18.6 |
| 5 | 609 | 646 | 6 | 10 | 11.1 |

Tree m_pedro526 had the highest mean productivity, with 471 fruits over three harvests (157.0 fruits harvest⁻¹). Two additional m_pedro trees and two aruana trees ranked among the five most productive individuals. Some trees with high mean productivity were observed in only two or three harvests; these cases require temporal confirmation before they can be classified as plus trees.

The ten trees with the highest cumulative production are presented in Table 6.

*Table 6. Ten trees with the highest cumulative fruit production, accounting for the number of monitored harvests.*

| **Rank** | **Clone** | **Tree** | **Total fruits** | **Harvests** | **Mean per harvest** |
|---|---|---|---|---|---|
| **1** | m_pedro | m_pedro526 | 471 | 3 | 157.0 |
| **2** | m_pedro | m_pedro539 | 430 | 3 | 143.3 |
| **3** | m_pedro | m_pedro527 | 757 | 6 | 126.2 |
| **4** | aruana | aruana537 | 525 | 5 | 105.0 |
| **5** | aruana | aruana534 | 498 | 6 | 83.0 |
| **6** | m_pedro | m_pedro509 | 327 | 5 | 65.4 |
| **7** | aruana | aruana522 | 384 | 6 | 64.0 |
| **8** | santa_fe | santa_fe517 | 300 | 5 | 60.0 |
| **9** | santa_fe | santa_fe505 | 289 | 5 | 57.8 |
| **10** | 606 | 606_561 | 288 | 5 | 57.6 |

Figure 3 presents the twenty trees with the highest cumulative production, identified by clone and number of monitored harvests.

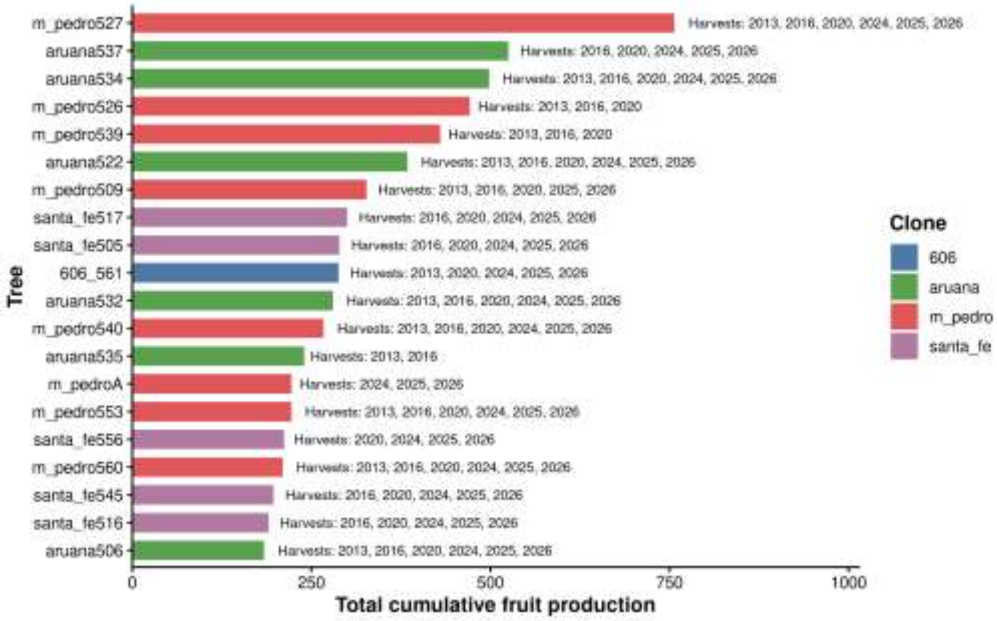


*Fig.3. Twenty trees with the highest cumulative fruit production, identified by clone and monitored harvests.*

*Source: Authors' data.*

### *Variance components*

Analysis of production variability showed that residual variation accounted for 51.6% of the variance on the transformed scale. Trees within clones accounted for 26.7%, slightly more than clones (21.7%). Clone identity is therefore relevant, but selection based solely on clone means would fail to capture a substantial component of among-tree variation.

Variance partitioning among clones, trees within clones, and residual variation is detailed in Table 7.

*Table 7. Variance components of fruit production on the log1p scale.*

| Component | Variance | Standard deviation | Contribution (%) |
|---|---|---|---|
| Clone | 0.375 | 0.612 | 21.74 |
| Tree within clone | 0.460 | 0.678 | 26.70 |
| Residual | 0.888 | 0.942 | 51.56 |

Figure 4 summarizes the relative contribution of fruit-production variance components.

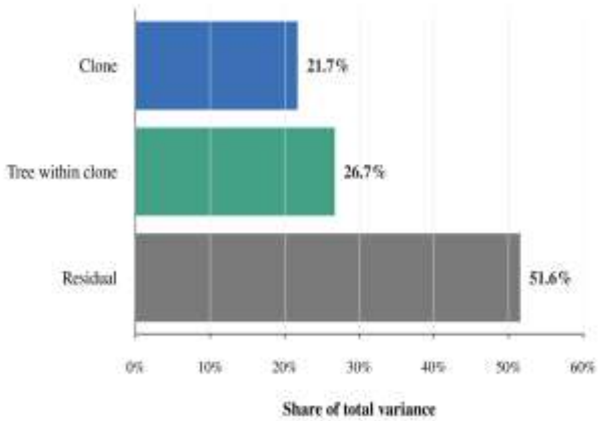


*Fig.4. Partitioning of fruit-production variability among clones, trees within clones, and residual variation.*

*Source: Authors' data.*

### Precipitation and fruit production

For total production, precipitation in the preceding year had a Pearson correlation of −0.030 ($p = 0.9002$; $n = 20$). The correlation with precipitation two years earlier was 0.240 ($p = 0.3888$; $n = 15$). Spearman correlations were also nonsignificant. Thus, at this annual resolution and with this sample, there was no evidence of a monotonic or linear relationship between total precipitation and fruit production.

## IV. DISCUSSION

### Implications for forest inventory and wood management

The performance of the double-entry Weibull equation demonstrates the operational benefit of measuring both DBH and height. Low bias and the similarity between fitting and cross-validation RMSE support its use within the sampled range (DBH 8.6–53.0 cm; height 11.1–29.0 m; age 9–23.5 years). Extrapolation to other sites, spacings, or thinning regimes requires external validation.

The volume estimates per hectare in Table 4 combine predicted individual-tree volume and the stand density recorded for each stratum. They do not constitute a yield curve and do not support reliable calculation of current or mean annual increment because the strata differ in composition and density. Nevertheless, they provide local inventory benchmarks and show that spacing and thinning decisions must consider both volume per tree and the number of residual trees. The literature shows that spacing affects diameter, biomass, volume, and crown architecture (Oliveira et al. 2021), attributes that may also influence fruit production.

The edaphic and topographic heterogeneity observed within the Agropecuária Aruanã plantations helps explain why stands of the same age may follow different growth trajectories. The Chapman–Richards model produced polymorphic site-index curves, and sand content and elevation were the main determinants of productivity, followed by K, Mn, and KCl pH (Souza et al. 2023). Transfer of the volume equation should therefore be accompanied by site stratification and independent validation.

As a regional benchmark, Marques et al. (2008) reported a mean annual increment of 23.69 $m^3\ ha^{-1}\ year^{-1}$ at age 10 in Amzonas. In the present study, mean annual increment was 30.5 $m^3\ ha^{-1}\ year^{-1}$ at the same age and 20.3 $m^3\ ha^{-1}\ year^{-1}$ at age 23.5 after thinning (Table 4). This comparison is descriptive because site, stand density, and silvicultural history differ between plantations; permanent-plot monitoring is needed to quantify future growth.

### Implications for fruit production

The cumulative superiority of clone m_pedro and the performance of trees m_pedro526, m_pedro539, m_pedro527, aruana537, and aruana534 identify these materials as priorities for continued monitoring, experimental propagation, and genetic evaluation. Cumulative production, however, does not automatically represent genetic value. Differences in crown exposure, within-stand position, neighborhood, soil, plant health, and management history are partly incorporated into the residual component.

The 26.7% contribution of among-tree variance within clones supports a two-stage strategy: selection of clones with high mean performance, followed by selection within those clones of trees with high production, representation across several harvests, and temporal stability. This procedure is consistent with studies recommending repeated measurements over time for selecting Brazil nut mother trees (Azevedo et al. 2020).

The benchmark of 41 fruits $tree^{-1}\ harvest^{-1}$ for clonal plantations (Passos et al. 2018) was exceeded by the ten most productive trees, whose means ranged from 57.6 to 157.0 fruits $tree^{-1}\ harvest^{-1}$ (Table 6). This comparison reinforces the potential for selection but should be interpreted in light of the unbalanced number of harvests recorded per individual.

### Climate and wood–fruit integration

The absence of correlation with annual precipitation does not imply the absence of climatic effects. Annual totals may obscure critical phenological windows, intra-annual rainfall distribution, water deficit, and temperature. Moreover, the small number of coincident years provides low statistical power. Studies based on longer time series have identified responses to seasonal rainfall and El Niño events (Rocha et al. 2021). Future analyses should model monthly rainfall and water deficit over periods preceding flowering, fruit development, and fruit fall.

In saplings, precipitation seasonality strongly altered carbon and nitrogen metabolism, whereas NPK addition promoted height and diameter growth, particularly in pure plantations; soluble sugars and amino acids appear to contribute to osmoregulation during dry periods (Oliveira et al. 2024). These mechanisms support the inclusion of monthly climatic variables and information on nutrition and planting system in future models, but they do not allow direct inference regarding fruit-production responses in adult trees.

This study separately demonstrates the wood-production potential of dense silvicultural plantations and strong reproductive differentiation in plantations managed for fruit production. This approach cannot determine whether larger-volume trees produce more or fewer fruits because individual trees could not be matched between datasets. Potential allocation trade-offs between vegetative growth and reproduction should be tested using a single dataset that includes DBH, height, crown dimensions, spatial position, clone, silvicultural interventions, and annual fruit production for each tree.

## V. RECOMMENDATIONS FOR PLANTATION MANAGEMENT

1. Use the double-entry Weibull equation for local inventories within the sampled range and perform independent validation before transferring it to other plantations.

2. Maintain periodic DBH and height measurements and explicitly record spacing, thinning, mortality, and residual stand density.

3. Prioritize m_pedro and aruana in comparative trials, without excluding less productive materials before assessing stability, adaptation, and genetic diversity.

4. Continue monitoring m_pedro526, m_pedro527, and the other superior trees over multiple harvests before recommending large-scale propagation.

5. Manage competition to maintain well-lit, functional crowns while jointly monitoring volume, crown dimensions, and fruit production.

6. Standardize tree identifiers and record climate, soil, plant health, and interventions to enable formal testing of management effects on wood and fruit production.

## VI. CONCLUSIONS

The evaluated plantation showed high dendrometric potential and broad reproductive heterogeneity. The Weibull equation based on DBH and height estimated total volume with good precision and internal stability and was therefore the preferred option for local inventories ($\hat{v} = 0.290468[1 - \exp\{-(d/43.159311)^{2.486072}\}]h^{0.653192}$, where $\hat{v}$ is in $m^3$, d is in cm, and h is in m). Clone m_pedro had the highest cumulative fruit production, whereas m_pedro526 had the highest mean production over three harvests.

Variation among trees within clones slightly exceeded variation among clones, supporting hierarchical selection at both levels. More than half of the variance remained residual, highlighting the need to include additional environmental and silvicultural covariates. The analyses detected no relationship between production and annual precipitation, but the short time series and annual aggregation preclude ruling out seasonal climatic effects.

The main research priority is an integrated, longitudinal, individual-tree experiment. Only repeated monitoring of the same trees will allow quantification of synergies or trade-offs between wood and fruit production and the definition of silvicultural regimes effectively designed for multiple use.

## VII. FUNDING

Amazonas State Research Support Foundation (FAPEAM), Program to Support Collaborative Research, Development, and Innovation Projects—Call 011/2022.

## VIII. LIMITATIONS

This study used cross-sectional data and two independent datasets. Management treatments were not allocated within an experimental design that would permit causal comparison of spacing, pruning, or thinning. Volumes per hectare represent specific strata rather than a controlled chronosequence. Fruit-production rankings are descriptive and partially unbalanced with respect to the number of harvests. The precipitation analysis includes few independent years and does not control for temperature, phenology, or autocorrelation. These limitations restrict causal inference but do not invalidate the use of the results to guide monitoring and formulate management hypotheses.

## ACKNOWLEDGEMENTS

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