

Balancing Accuracy and Efficiency: Optimal Plot Design for Regeneration Sampling in Amazonian Secondary Forests

Bruno Barbosa Boás^{1*}, Vitor Mateus de Carvalho Morais¹, Divino Vicente Silvério²,
Fabiano Emmert¹, Rodrigo Geroni Mendes Nascimento¹

¹Federal Rural University of Amazonia, Institute of Agricultural Sciences, Laboratory of Mensuration and Management of Forest Resources, Belém, Pará, Brazil

²Federal Rural University of Amazonia, Capitão Poço Campus, Laboratory of Geotechnologies and Software Production, Capitão Poço, Pará, Brazil

FOREST MANAGEMENT

ABSTRACT

Background: Optimal sampling designs are crucial for accurate ecological and forestry assessments, particularly for regeneration studies in Amazonian secondary forests, which play an important role in biodiversity conservation and carbon sequestration. This study evaluated different sampling plot configurations for estimating regeneration diversity and structural attributes in a 30-year-old secondary forest in Belém, Brazil. Within a one-hectare permanent plot (100 × 100 m), all trees with a diameter at breast height (DBH) ≤ 10 cm were measured, identified, and geolocated, totaling 3,003 individuals. Trees were classified into two diameter classes: DBH < 5 cm and 5 cm ≤ DBH ≤ 10 cm. Resampling simulations using the bootstrap method subdivided the one-hectare plot into four sampling plot sizes (4 m², 25 m², 50 m², and 100 m²) with rectangular and square shapes. Simulations tested sample sizes ranging from four to (N – 1) units, with 1,000 iterations per configuration.

Results: Accuracy and precision for diversity metrics (species richness and Shannon–Weaver index) and structural attributes (tree density, stem density, and basal area) were evaluated using Mean Absolute Error (MAE) and Relative Sampling Error (RSE). Results indicated that 4 m² sampling plots were the most suitable for estimating diversity metrics across both diameter classes, regardless of plot shape. For structural variables, square 4 m² plots performed best for trees with DBH < 5 cm, whereas rectangular 50 m² plots were optimal for trees with 5 cm ≤ DBH ≤ 10 cm. The influence of plot shape varied depending on the variable analyzed and the sampling plot size.

Conclusion: Overall, sampling plots of 4 m² and 50 m² are recommended for efficient regeneration sampling in Amazonian secondary forests, as they provide better accuracy and precision for diversity and structural estimates across different diameter classes.

Keywords: Forest inventory; sampling simulation; urban forest; forest degradation.

HIGHLIGHTS

The permanent plot establishment enables monitoring of forest regeneration.
Simulations identify efficient sampling plot sizes to optimize inventory accuracy and precision.
Data analysis highlights regeneration patterns and forest structure dynamics.
Square plots of 4 m² and rectangular plots 50 m² enhance accuracy in forest inventory sampling.

BOÁS, B. B.; MORAIS, V. M. C.; SILVÉRIO, D. V.; EMMERT, F.; NASCIMENTO, R. G. M.. Balancing Accuracy and Efficiency: Optimal Plot Design for Regeneration Sampling in Amazonian Secondary Forest. CERNE, v. 32, e103599, 2026. DOI: 10.1590/01047760202632013599

INTRODUCTION

Secondary forests are critical ecosystems undergoing regeneration after severe natural or anthropogenic disturbances (Chokkalingam and De Jong, 2001). These disturbances often compromise essential ecosystem services, such as biodiversity conservation (Arasa-Gisbert *et al.*, 2024) and carbon sequestration (Bullock and Woodcock, 2021; Pan *et al.*, 2024). In the Amazon region, the transition from old-growth forests to less carbon-dense secondary forests, driven by deforestation and degradation (Smith *et al.*, 2021), poses a significant challenge to the region's role in mitigating climate change (Qin *et al.*, 2021). Addressing these challenges requires an understanding of the ecological dynamics of forest regeneration and the development of strategies to optimize the restoration of ecosystem functions.

Forest restoration has emerged as a central approach to reestablishing the carbon storage capacity and biodiversity of secondary forests, thereby ensuring the long-term sustainability of ecosystem services (Bieng *et al.*, 2021). Restoration success is measured against benchmarks derived from mature or older secondary forests, which serve as reference points to guide the recovery process (Shackelford *et al.*, 2024; Chazdon *et al.*, 2023). Attributes such as species composition, biodiversity indices, tree density, basal area, biomass, and abiotic conditions underpin restoration objectives (Giles *et al.*, 2024).

Regeneration, defined as the recovery of richness, structure, and functional traits in disturbed forests, is a pivotal aspect of forest restoration (Hanbury-Brown; Ward; Kueppers, 2022). Small-diameter trees play a crucial role in regeneration, often relying on canopy gaps for growth, although some species can persist under shaded conditions (Swaine; Whitmore, 1988). Evaluating the diversity and structural characteristics of regenerating trees helps determine the resilience of secondary forests and provides insights into whether they can retain their ecological integrity (Brasil Neto *et al.*, 2021; Zébazé *et al.*, 2023). However, one of the challenges in assessing regeneration is optimizing inventory methods to strike a balance between precision and efficiency.

Forest inventories are indispensable tools for quantifying forest regeneration and growth. Their effectiveness depends on appropriate sampling plot configurations, specifically size and shape, which directly affect sampling accuracy and cost efficiency (Lister; Leites, 2021; Pinto *et al.*, 2021). Recent advancements in methodologies, such as UAV-borne laser scanning highlighted by Sferlazza *et al.* (2022), show promise for refining sampling techniques and enabling enhanced monitoring of forest dynamics. This study demonstrates how technology-based approaches can complement traditional inventories, particularly in areas with complex topographies and dense canopies.

Seedling growth stages and environmental conditions further influence the dynamics of tree regeneration. Harris *et al.* (2022) emphasize the importance of subdividing seedlings into height classes to better predict sapling recruitment, as taller seedlings are more likely to contribute to forest recovery. Incorporating this

approach into regeneration assessments improves the accuracy of forecasting stand development trajectories. Additionally, permanent plots are essential for monitoring tree communities, allowing the capture of ecological and structural changes that can inform restoration strategies (Phillips, 2023). The relationship between seedling diversity and regeneration is also assessed using rarefaction and extrapolation techniques (Chiu, 2023). These statistical methods enhance the reliability of regeneration estimates and ensure adequate representation of tree species, even in highly diverse ecosystems like the Amazon. Integrating such advanced analytical tools into inventory designs can bridge gaps in understanding regeneration dynamics.

This study seeks to address the critical question: What are the optimal plot configurations for assessing regeneration diversity and structural variables in tropical secondary forests? Comparing optimal plot size and shape, and drawing on prior literature and recent advancements, the research hypothesizes that larger plot sizes minimize sampling errors and that square-shaped plots yield more consistent estimates of diversity and density. By focusing on regeneration processes and inventory optimization, the findings aim to inform evidence-based practices for restoring secondary forests and enhancing their contributions to mitigating global climate change.

MATERIAL AND METHODS

Study Area

The study area corresponds to a secondary urban forest that has undergone natural regeneration for approximately six decades following experimental land use and subsequent abandonment (Terezo, 2014; Guzmán, 2022). Although exhibiting structural and compositional attributes typical of mid- to late-successional forests, the site remains subject to low-to-moderate anthropogenic disturbance due to its urban context. The forest located near the Institute of Agricultural Sciences (ICA) at the Federal Rural University of Amazonia (UFRA) in Belém, Pará, Brazil. The central point of the experimental area is situated at coordinates 1°27'24"S and 48°26'15"W. This forest represents a tropical humid ecosystem with an average annual temperature of 27°C and rainfall of approximately 2,834 mm, classified as Af by the Köppen-Geiger system. The predominant soil type is a concretionary laterite alisol with low base saturation (Santos *et al.*, 1983). The experimental area has been planned for a permanent plot establishment since 2017 and has been remeasured annually to monitor forest dynamics and regeneration.

Installation of the Experimental Area

An aerial georeferenced image produced by a drone in 2017 was used for inventory planning. The high-resolution image, with spatial resolution at the centimeter scale typical of UAV surveys, projected in UTM coordinates, facilitated the delineation and analysis of the study area. The site was

selected for its lack of flooding during rainy periods and its well-established natural regeneration. A permanent plot measuring 1-hectare (100 m x 100 m) was installed using a *Ruide R2* Total Station to accurately define the external boundaries and internal subdivisions. The permanent plot was subdivided into 4 blocks (50 m x 50 m), each containing 25 subplots (10 m x 10 m), for a total of 100 subplots. Topographic stakes were placed at each vertex to ensure durability and ease of relocation for future assessments. Subplot divisions were performed manually through geometric triangulation, using two 50 m measuring tapes simultaneously to position each vertex based on fixed distances to adjacent and perpendicular reference points, ensuring accurate 10 × 10 m subplot layout despite challenging field conditions

Data Collection

The inclusion criterion for the forest inventory was trees less than 1.3 m in height and with a diameter at breast height (DBH) \leq 10 cm, classified as natural regeneration to distinguish these juvenile individuals from the mature population. Data collection was organized by grouping subplots into strips, with each strip consisting of five subplots (10 m x 50 m). Measurements followed a systematic path along these strips. In each subplot, we measured all stems meeting the inclusion criteria, and the subsequent analysis divided this data into the number of trees per hectare (D) and the number of stems per hectare (D_s), as some individuals had more than one stem.

A digital caliper was used for stems with a diameter at breast height (DBH) \leq 5 cm, and a measuring tape was used for stems with a DBH $>$ 5 cm. Measurements included quantitative variables (DBH, XY coordinates, basal area) and qualitative variables (health condition, crown illumination, stem classification). Each individual was marked with red oil-based paint at the measurement height for future remeasuring, and identification numbers were assigned using plastic tags. Botanical identification was primarily conducted in the field with the help of a parobotanist, and the trees not identified by this method were collected and dried for subsequent identification using field guides and other specialized literature.

Georeferencing and Sampling Simulations

All field data were digitized and subsequently organized into a geospatial database. Cartesian coordinates for each tree were adjusted to match their true positions within the plot. Georeferencing utilized "control points" placed at the plot vertices, ensuring spatial accuracy for further analysis. The geospatial database facilitated the visualization and manipulation of tree distribution and characteristics across the study area. For the regeneration sampling, we divided the database into two groups: trees with DBH $<$ 5 cm and trees with 5 cm \leq DBH \leq 10 cm, to identify the best plot configuration for each diameter class. Resampling simulations using the bootstrap method were conducted with a fixed-area random sampling design,

dividing the 1 ha plot into four smaller plot sizes (4 m², 25 m², 50 m², and 100 m²), with square and rectangular plot shapes, resulting in eight different plot configurations. We selected these sampling plot sizes to optimize the 1-ha permanent plot area and because they had already been used in previous studies. Simulations tested sample sizes from four to (N - 1) units, with 1000 iterations per configuration, and not discarding zero-plots, plots without trees, from the simulated samples. Simulations were performed using R, and statistical metrics, including mean, variance, mean absolute error (MAE), and relative sampling error (RSE), were calculated. The acceptable sampling error was 10%, a technical standard widely used in tropical forest inventories and frequently required in environmental licensing processes in the Amazon.

Data Analysis

Five key variables were analyzed: the number of trees per hectare (D), the number of stems per hectare (D_s), basal area (G), richness, and the Shannon-Weaver index. Estimates were extrapolated for a 1-hectare scale. Statistical analyses were conducted to evaluate the accuracy and precision of various sampling designs, with the aim of optimizing efficiency while ensuring compliance with technical and ecological standards. The results were organized by creating graphs comparing the MAE and RSE with the sampled area to assess their impact on precision and accuracy. This allowed us to determine which plot required less sampling intensity to achieve the lowest MAE and an RSE of 10%, the standard in forestry practices for the Amazon. The diversity variables were compared with the sampled area for the same purpose.

RESULTS

The total count of individual stems measured in the 1 ha plot was 4406, of which 3647 had DBH $<$ 5 cm and 759 had 5 cm \leq DBH \leq 10 cm, while the basal area of the plot was equal to 4.51 m² ha⁻¹ for all stems. These stems belong to 3003 trees in total, distributed across 40 botanical families, 67 genera, and 87 species (Table 1). The families with the highest richness were Fabaceae (18 species), Myrtaceae (6 species), and Annonaceae (4 species). Sapindaceae (4 species) and Burseraceae (4 species). More than half of the families (22) had only one species in the 1-ha permanent plot. The genus with the most species was *Inga* Mill. (8 species), *Protium* Burm.f. (4 species) and *Eugenia* L. (4 species), with the remaining genera having two or one species.

The families with the highest D were Lecythidaceae (552 trees), Nyctaginaceae (356 trees), Fabaceae (323 trees), Myrtaceae (205 trees), and Boraginaceae (203 trees). The genus with the highest D was *Gustavia* L. (533 trees), *Neea* Ruiz & Pav. (307 trees), *Inga* Mill. (225 trees), *Cordia* L. (203 trees) and *Eugenia* L. (200 trees). The species with the highest D value was *Gustavia augusta* L. (534 trees), and *Neea floribunda* Poepp. & Endl. (307 trees), *Cordia bicolor* A.DC. (202 trees), *Guarea guidonia* (L.) Sleumer (182 trees), and *Siparuna guianensis* Aubl. (170 trees).

Table 1: Structural variables of the trees (DBH ≤ 10 cm) measured in the 1 ha plot of Amazon secondary forest situated in Belém, State of Pará, Brazil. D – Tree density, DS – Stem density, G – Basal area (m².ha-1), NI – Not identified.

Family/Species	D	Ds	G
Anacardiaceae	79	83	0.128553
<i>Tapirira guianensis</i> Aubl.	79	83	0.128553
Annonaceae	23	31	0.050151
<i>Annona muricata</i> L.	9	10	0.015343
<i>Duguetia cauliflora</i> R.E.Fr.	2	3	0.002701
<i>Duguetia marcgraviana</i> Mart.	1	1	0.007451
<i>Guatteria punctata</i> (Aubl.) R.A.Howard	11	17	0.024656
Apocynaceae	8	13	0.002788
<i>Tabernaemontana siphilitica</i> (L.f.) Leeuwenb.	8	13	0.002788
Araliaceae	5	5	0.01019
<i>Schefflera morototoni</i> (Aubl.) Maguire et al.	5	5	0.01019
Arecaceae	2	2	0.00007
<i>Euterpe oleracea</i> Mart.	2	2	0.00007
Bignoniaceae	5	5	0.008264
<i>Jacaranda copaia</i> (Aubl.) D.Don	5	5	0.008264
Boraginaceae	203	225	0.281599
<i>Cordia bicolor</i> A.DC.	202	224	0.280853
<i>Cordia nodosa</i> Lam.	1	1	0.000746
Burseraceae	18	24	0.019821
<i>Protium altsonii</i> Sandwith	3	4	0.000364
<i>Protium amazonicum</i> (Cuatrec.) Daly	10	14	0.017817
<i>Protium apiculatum</i> Swart	4	5	0.001541
<i>Protium</i> sp.	1	1	0.000099
Calophyllaceae	4	4	0.005962
<i>Calophyllum brasiliense</i> Cambess.	4	4	0.005962
Caryocaraceae	1	1	0.000050
<i>Caryocar glabrum</i> (Aubl.) Pers.	1	1	0.000050
Chrysobalanaceae	25	28	0.030072
<i>Licania guianensis</i> (Aubl.) Griseb.	1	1	0.000845
<i>Licania</i> sp.	22	25	0.025686
<i>Parinari excelsa</i> Sabine	2	2	0.003541
Clusiaceae	3	3	0.000895
<i>Garcinia gardneriana</i> (Planch. & Triana) Zappi	2	2	0.000381
<i>Symphonia globulifera</i> L.f.	1	1	0.000515
Dichapetalaceae	1	1	0.000491
<i>Tapura guianensis</i> Aubl.	1	1	0.000491
Ebenaceae	2	2	0.003115
<i>Diospyros artanthifolia</i> Mart.	2	2	0.003115
Erythroxylaceae	1	1	0.000012
<i>Erythroxylum acuminatum</i> Ruiz & Pav.	1	1	0.000012
Euphorbiaceae	7	8	0.017128
<i>Sloanea grandiflora</i> Sm.	7	8	0.017128
Fabaceae	323	418	0.474309
<i>Abarema jupunba</i> (Willd.) Britton & Killip	2	2	0.000072
<i>Apuleia leiocarpa</i> (Vogel) J.F. Macbr.	8	8	0.033688

Continue...

Table 1: Continuation.

Family/Species	D	Ds	G
<i>Calliandra surinamensis</i> Benth.	67	105	0.095504
<i>Cassia fastuosa</i> Willd. ex Benth.	3	3	0.000436
<i>Inga alba</i> (Sw.) Willd.	35	36	0.015305
<i>Inga cayennensis</i> Sagot ex Benth.	54	76	0.131195
<i>Inga edulis</i> Mart.	54	65	0.054475
<i>Inga heterophylla</i> Willd.	41	46	0.040107
<i>Inga rubiginosa</i> (Rich.) DC.	26	31	0.048334
<i>Inga</i> sp.	8	16	0.016566
<i>Inga thibaudiana</i> DC.	1	1	0.000033
<i>Inga velutina</i> Wild.	6	6	0.004126
<i>Pentaclethra macroloba</i> (Willd.) Kuntze	2	5	0.007264
<i>Pseudopiptadenia suaveolens</i> (Miq.) J.W.Grimes	1	1	0.005215
<i>Stryphnodendron pulcherrimum</i> (Willd.) Hochr.	6	7	0.005169
<i>Swartzia laurifolia</i> Benth.	7	8	0.013031
<i>Swartzia polyphylla</i> DC.	1	1	0.000311
<i>Tachigali myrmecophila</i> (Ducke) Ducke	1	1	0.003476
Lacistemataceae	9	12	0.025476
<i>Lacistema pubescens</i> Mart.	9	12	0.025476
Lamiaceae	6	14	0.018251
<i>Vitex triflora</i> Vahl	6	14	0.018251
Lauraceae	114	177	0.208693
<i>Nectandra cuspidata</i> Nees	82	137	0.151681
<i>Ocotea guianensis</i> Aubl.	8	9	0.006893
<i>Ocotea</i> sp.	24	31	0.050119
Lecythidaceae	552	1242	1.272215
<i>Gustavia augusta</i> L.	534	1222	1.249252
<i>Lecythis pisonis</i> Cambess.	18	20	0.022963
Malvaceae	2	2	0.004568
<i>Sterculia pruriens</i> (Aubl.) K.Schum.	2	2	0.004568
Melastomataceae	100	135	0.138258
<i>Bellucia</i> sp.	1	1	0.000962
<i>Miconia fallax</i> DC.	99	134	0.137296
Meliaceae	182	279	0.288893
<i>Guarea guidonia</i> (L.) Sleumer	182	279	0.288893
Moraceae	19	20	0.012447
<i>Brosimum lactescens</i> (S.Moore) C.C.Berg	14	15	0.009134
<i>Clarisia racemosa</i> Ruiz & Pav.	4	4	0.003308
<i>Ficus maxima</i> Mill.	1	1	0.000005
Myristicaceae	77	82	0.14646
<i>Virola sebifera</i> Aubl.	42	43	0.088319
<i>Virola surinamensis</i> (Rol. ex Rottb.) Warb.	35	39	0.058142
Myrtaceae	205	247	0.189709
<i>Eugenia biflora</i> (L.) DC.	151	180	0.153703
<i>Eugenia cupulata</i> Amshoff	1	1	0.00019
<i>Eugenia patrisii</i> Vahl	28	39	0.023902

Continue...

Table 1: Continuation.

Family/Species	D	Ds	G
<i>Eugenia</i> sp.	19	20	0.008535
<i>Myrcia splendens</i> (Sw.) DC.	6	7	0.00085
NI	218	269	0.099616
NI	218	269	0.099616
Nyctaginaceae	356	488	0.334749
<i>Guapira opposita</i> (Vell.) Reitz	49	76	0.021268
<i>Neea floribunda</i> Poepp. & Endl.	307	412	0.313481
Ochnaceae	3	6	0.002908
<i>Ouratea castaneifolia</i> (DC.) Engl	3	6	0.002908
Peraceae	8	11	0.000507
<i>Chaetocarpus echinocarpus</i> (Baill.) Ducke	8	11	0.000507
Piperaceae	9	11	0.000651
<i>Piper aduncum</i> L.	9	11	0.000651
Rubiaceae	5	5	0.000847
<i>Coffea</i> sp.	1	1	0.00038
<i>Palicourea guianensis</i> Aubl.	3	3	0.00045
<i>Psychotria</i> sp.	1	1	0.000017
Salicaceae	4	5	0.014394
<i>Casearia arborea</i> (Rich.) Urb.	4	5	0.014394
Sapindaceae	166	210	0.224668
<i>Cupania scrobiculata</i> Rich.	86	113	0.142803
<i>Paullinia</i> sp.	1	2	0.000257
<i>Sapindus saponaria</i> L.	63	77	0.065419
<i>Talisia acutifolia</i> Radlk.	16	18	0.016189
Sapotaceae	26	30	0.030639
<i>Pouteria guianensis</i> Aubl.	6	7	0.013796
<i>Pouteria macrophylla</i> (Lam.) Eyma	20	23	0.016843
Simaroubaceae	34	36	0.04525
<i>Simarouba amara</i> Aubl.	34	36	0.04525
Siparunaceae	170	233	0.387443
<i>Siparuna guianensis</i> Aubl.	170	233	0.387443
Urticaceae	11	18	0.03124
<i>Cecropia distachya</i> Huber	10	17	0.024822
<i>Cecropia</i> sp.	1	1	0.006418
Violaceae	16	19	0.006138
<i>Paypayrola grandiflora</i> Tul.	1	3	0.002732
<i>Rinorea pubiflora</i> (Benth.) Sprague & Sandwith	15	16	0.003407
Vochysiaceae	1	1	0.000085
<i>Vochysia guianensis</i> Aubl.	1	1	0.000085
Total	3003	4406	4.515274

The species richness was 83 for trees with $DBH < 5$ cm and 55 for trees with $5 \text{ cm} \leq DBH \leq 10$ cm. In both classes, species richness increased linearly with sampled area, with little variation in estimates across the sampling plot sizes and shapes tested (Figs. 1A and 2A). Regardless of the sampling plot configuration, a sampled area of 0.87 to 0.95 ha for $DBH < 5$ cm, and 0.85 to 0.95 ha for $5 \text{ cm} \leq DBH \leq 10$ was necessary to obtain the parametric value of richness.

The Shannon–Weaver index was 3.21 nats/ind. for trees with $DBH < 5$ cm and 3.16 for trees with $5 \text{ cm} \leq DBH \leq 10$ cm. In this variable, the sampling showed slightly more variation than in richness. For trees with $DBH < 5$ cm, to obtain the parametric value, an inventory using rectangular or square 4 m^2 sampling plots requires 0.66 ha of sampled area. In comparison, a rectangular or square 100 m^2 sampling plot requires around 0.85 – 0.86 ha (Fig. 1B). As for trees with $5 \text{ cm} \leq DBH \leq 10$ cm there is a slight increase in sampling area, for a rectangular or square 4 m^2 plots 0.70 – 0.71 ha are necessary, while for rectangular or square 100 m^2 the sampled area is around 0.88 – 0.90 ha (Fig. 2B). Thus, plot shape also has little influence on the sampled area necessary for this variable.

The D of our 1 ha plot totaled 2389 trees with $DBH < 5$ cm, and MAE analysis showed that the 4 m^2 sampling plot yields the best results, with an increase in sampling plot size also showing an increase in error (Fig. 3A). Also, using rectangular or square plots has little influence on sampling accuracy. For the $5 \text{ cm} \leq DBH \leq 10$ cm diameter class, D was equal to 614 trees, and the 4 m^2 sampling plot also had the best results. However, unlike the $DBH < 5$ cm diameter class, the sampled area has a greater influence on accuracy (Fig. 4A). Again, the results are independent of plot shape.

The D_s for the trees with $DBH < 5$ cm were 3647 stems; the smaller sampling plots were the most precise (Fig.

3B), with the 4 m^2 sampling plot being the most accurate. In this case, plot shape influenced the results, with a square plot yielding better accuracy for all plot sizes. For trees with $5 \text{ cm} \leq DBH \leq 10$ cm, the D_s was 759 stems, and the results were quite different, with greater accuracy obtained by the rectangular 50 m^2 sampling plot, while the 4 m^2 had the worse results, followed by the 25 m^2 and 100 m^2 , for these the rectangular shape also had the best results, except for the 4 m^2 sampling plot where the square shape was better (Fig. 4B).

G for the $DBH < 5$ cm diameter class was 1.6077 m^2 , and the smaller sampling plots performed better, with the square 4 m^2 sampling plot being the best. Except for this sampling plot size, the influence of plot shape was minimal (Fig. 3C). As for the $5 \text{ cm} \leq DBH \leq 10$ cm diameter class, G was equal to 2.9074 m^2 , and the results were similar to the D_s variable, with the rectangular 50 m^2 sampling plot being the best overall, and the rectangular shape yielding better results for 100 m^2 and 25 m^2 sampling plots, and the square shape for the 4 m^2 sampling plot (Fig. 4C). For both diameter classes the accuracy of G is dependent on the total sampled area. However, for $DBH < 5$ cm, this occurs only with the 4 m^2 sampling plots.

The RSE results of D for the $DBH < 5$ cm diameter class show that smaller sampling plots need less sampled area to achieve the 10% threshold, with 0.16 ha for the 4 m^2 sampling plot and 1.79 ha for the 100 m^2 sampling plot (Fig. 5A). As for the diameter class of $5 \text{ cm} \leq DBH \leq 10$ cm, the sampling plot that needs less sampled area to achieve a RSE of 10% was the 25 m^2 sampling plot, with 0.39 ha, followed by the 50 m^2 sampling plot, 0.49 – 0.50 ha, the 4 m^2 sampling plot, 0.53 ha, and lastly by the 100 m^2 sampling plot, 0.90 ha (Fig. 6A). For both diameter classes, there was little influence of the sampling plot shape.

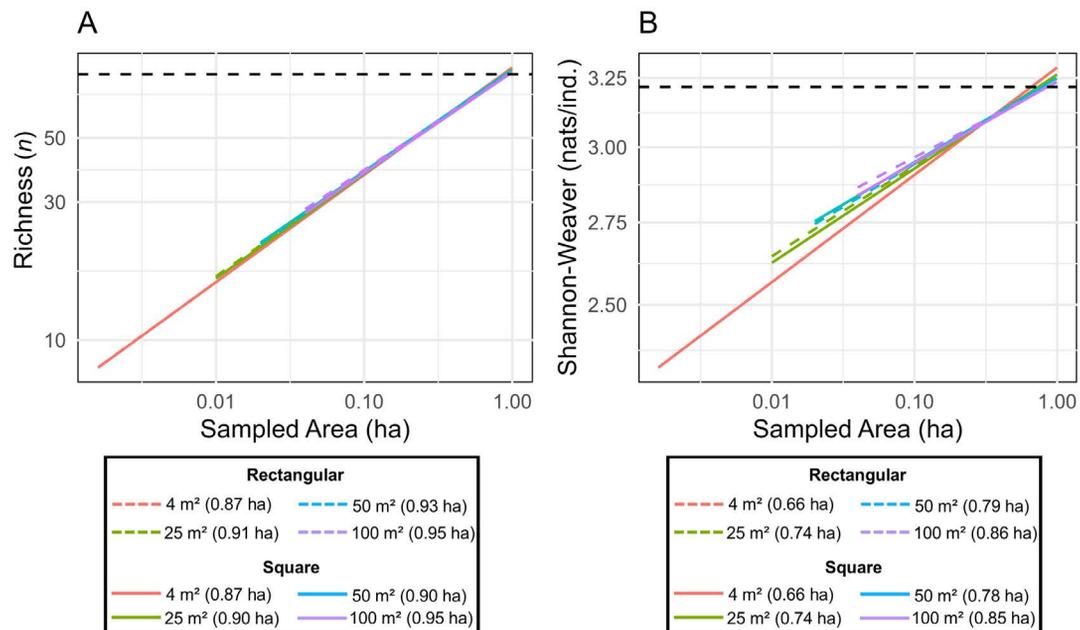


Figure 1: Ecological variables of trees with $DBH < 5$ cm in a one-hectare sampled area. A – richness; B – Shannon–Weaver index. The graphs are on a logarithmic scale to facilitate visualization, and the horizontal dashed black line indicates the parametric value of each variable.

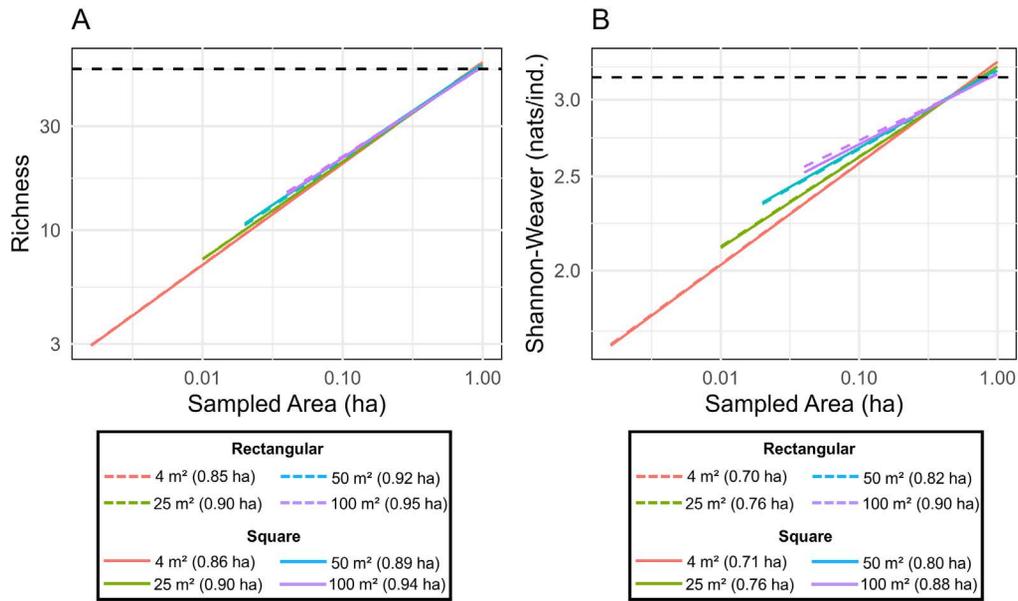


Figure 2: Ecological variables of trees with $5\text{ cm} \leq \text{DBH} \leq 10\text{ cm}$ in a one-hectare sampled area. A – richness; B – Shannon–Weaver index. The graphs are on a logarithmic scale to facilitate visualization, and the horizontal dashed black line indicates the parametric value of each variable.

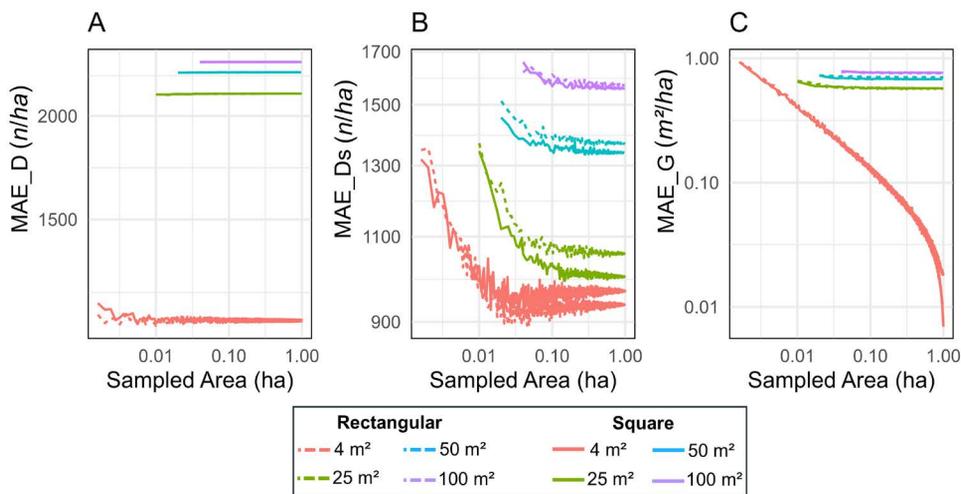


Figure 3: Mean Absolute Error (MAE) of the structural variables of the $\text{DBH} < 5\text{ cm}$ diameter class in the 1 ha plot in relation to the sampled area. A – Tree density, B – Stem density, and C – Basal area. MAE – Mean Absolute Error, D – Tree density, D_s – Stem density, G – Basal area. The graphs are on a logarithmic scale to facilitate visualization.

The results of D_s for trees with $\text{DBH} < 5\text{ cm}$ (Fig. 5B) follow the same trend: the 4 m^2 sampling plot requires only 0.08 ha to achieve an RSE of 10%, while the 100 m^2 sampling plot requires $1.81 - 1.83\text{ ha}$ to achieve the same precision. The influence of plot shape was minimal for this diameter class. As for the $5\text{ cm} \leq \text{DBH} \leq 10\text{ cm}$ diameter class, less sampled area is necessary, 0.01 ha for the 4 m^2 sampling plot and around $1.19 - 1.34\text{ ha}$ for the 100 m^2 sampling plot (Fig. 6B). There was a small influence of plot shape, with the biggest difference being in the 100 m^2 where the square sampling plot needs 0.15 ha less to achieve the 10% threshold.

For G in the $\text{DBH} < 5\text{ cm}$ diameter class, the 4 m^2 sampling plot needs 0.24 ha of sampled area, and the 100 m^2 sampling plot needs 1.80 ha (Fig. 5C). The plot shape also does not have much influence on its results. For the $5\text{ cm} \leq \text{DBH} \leq 10\text{ cm}$ class, the most effective sampling plot was the square 4 m^2 one with a total sampled area of 0.59 ha . This was followed by the rectangular 25 m^2 sampling plot with 0.61 ha and the rectangular 4 m^2 sampling plot with 0.64 ha (Fig. 6C). The 50 m^2 sampling plot requires 0.78 ha independent of shape, and the 100 m^2 sampling plot requires 1.21 ha for the square shape and 1.46 ha for the rectangular shape. A summary of the RSE% results is presented at Table 2.

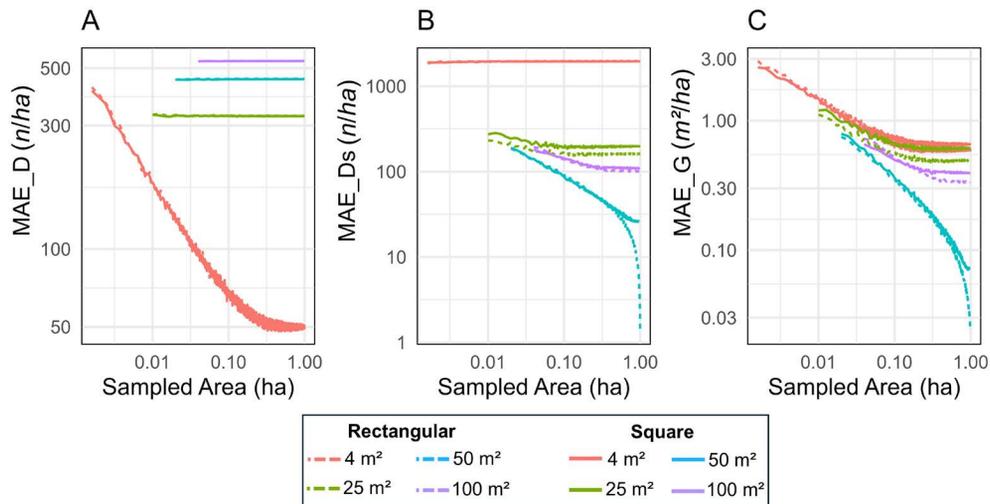


Figure 4: Mean Absolute Error (MAE) of the structural variables of the 5 cm ≤ DBH ≤ 10 cm diameter class in the 1 ha plot in relation to the sampled area. A – Tree density, B – Stem density, and C – Basal area. MAE – Mean Absolute Error, D – Tree density, D_s – Stem density, G – Basal area. The graphs are on a logarithmic scale to facilitate visualization.

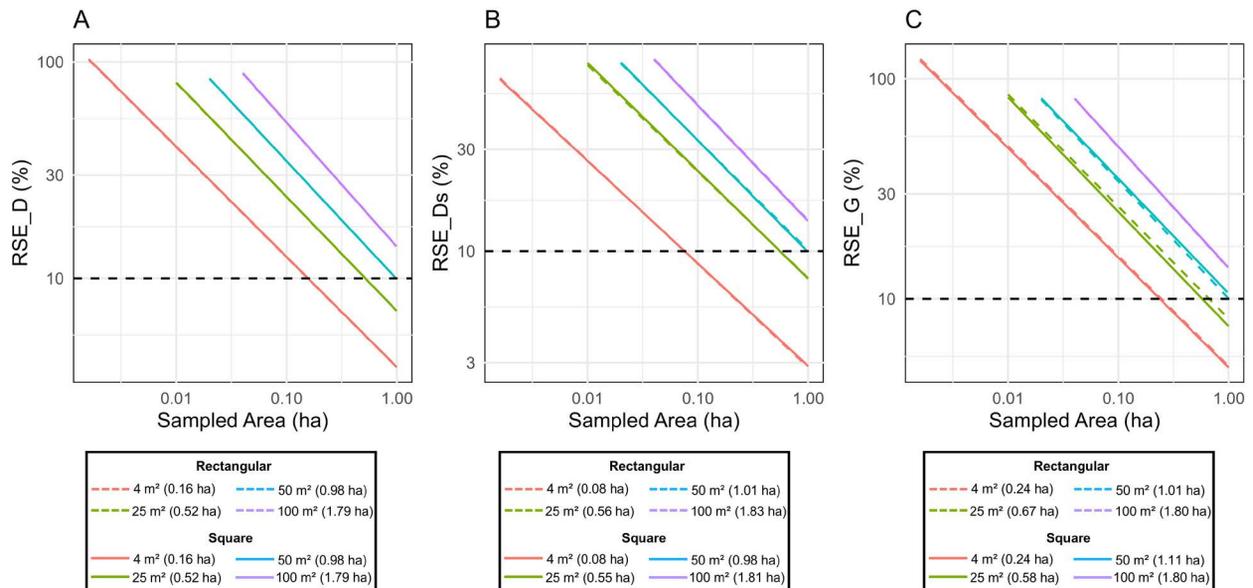


Figure 5: Relative Sampling Error (RSE) of the structural variables of the DBH < 5 cm diameter class in the 1 ha plot in relation to the sampled area. A – Tree density, B – Stem density, and C – Basal area. RSE – Relative Sampling Error, D – Tree density, D_s – Stem density, G – Basal area. The graphs are plotted on a logarithmic scale to facilitate visualization, and the horizontal black dashed line indicates a relative standard error (RSE) of 10%.

DISCUSSION

Overall, the diameter distribution for natural regeneration followed a negative exponential curve, indicative of uneven-aged native forests, and the basal area of 4.51 m².ha⁻¹ closely aligns with estimates from Vieira et al. (2021) in sites under regeneration in an ombrophilous dense forest (3.5 – 9.35 m².ha⁻¹). These findings corroborate the established patterns of regeneration dynamics under light and environmental constraints outlined by Swaine and

Whitmore (1988). The results of families with the highest richness, Fabaceae, Myrtaceae, Annonaceae, Sapindaceae, and Burseraceae, show a common pattern in the Amazon region, notably for the Fabaceae family, which ranks first in several studies (Draper et al., 2021; Colli-Silva; Pirani, 2022).

When considering the regeneration diversity, a single smaller plot will produce a less accurate estimate than a single larger plot; however, all plot sizes and shapes can accurately estimate the diversity variables with the appropriate sampled area. In this case, the decision regarding

the ideal sampling plot size and shape is based on the time and cost constraints of the different plot configurations, as well as operational practicalities. Some studies agree with our findings of similarity in the estimation of forest diversity using different sampling plot sizes and shapes (Pinto et al., 2021; Bernardes-da-Silveira, 2022), whereas others show a clear influence of plot configuration in forest diversity assessment, which recommends the use of large plot sizes because of their influence on obtaining more species and individuals, thus estimating diversity and evenness indices with greater precision (Chazdon et al., 2023; Kardgar et al., 2024); therefore, these factors must be accounted if the study includes diversity analysis. As for plot shape, the literature is mixed, with some studies showing that rectangular plots can yield more species (Condit et al., 1996; Bacaro et al., 2015), while others indicate that this increase is modest (Laurance et al., 1998; Keeley; Fotheringham, 2005).

As for the forest regeneration structure, an increase in accuracy with an increase in sampled area for the *G* variable has been reported in other studies (Ubialli et al., 2009; Augustynczyk et al., 2013). Although, the same trend for *D*, in the 5 cm ≤ DBH ≤ 10 cm diameter class, appears to be a novelty of our study as a lack of influence of the sampled area on the accuracy of *D* is commonly registered (Augustynczyk et al., 2013), similar to what happened to the DBH < 5 cm diameter class in our analysis. However, it is essential to note that these studies sampled different tree size classes and employed far fewer simulations than ours, making it challenging to discern general trends.

In the few studies regarding the ideal plot size for structural sampling in tropical forest regeneration, the larger plots yield the best results, with the optimal plot size being between 70 m² and 100 m² due to lesser gain in accuracy for sampling plots larger than this (Gnonlonfoun et al. 2015,

Hounsode et al. 2015). Our results were somewhat mixed, with the use of a smaller 4 m² or a larger 50 m² sampling plot depending on the diameter class and variable sampled. The use of a larger plot has the advantage of producing a lower variance between plots, so fewer plots can achieve the same level of precision as several small plots, which reduces the commute time between plots (Zeide 1980; Evans and Viengkham, 2001; Bernardes-da-Silveira et al. 2022); however, more time is spent inventorying trees within a larger plot (Zeide, 1980; Pinto et al., 2024).

Overall, the plot shape influenced the estimation of the regeneration structure across all plot sizes tested, with a square or rectangular plot being the most accurate, depending also on the diameter class, variable, and plot size sampled. The literature on this topic also has mixed conclusions, with greater efficiency found in square plots (Salako et al., 2013; Roveda et al., 2016), rectangular plots (Gnonlonfoun et al., 2015; Hounsode et al., 2015), and neither plot shape (Evans and Viengkham, 2001; Oliveira et al., 2014). These mixed findings are due to the ideal plot shape being dependent on factors such as the spatial distribution of trees and the forest's environmental gradient (Gnonlonfoun et al., 2015), which are beyond the scope of our study.

When considering sampling precision, our results indicate that smaller plots obtain estimates of the variables with a sampling error of 10% for a lower sampled area. Generally, in forest mensuration activities within natural forests, smaller plots tend to produce more variance than larger plots (Pinto et al., 2021; Musa et al., 2025). However, when using statistics such as the RSE and the standard error, which the former uses in its equation, at any sampled area, the variance in small plots is divided by more sample units than in large plots, which explains why smaller plots reach the desired RSE with less sampled area (Kershaw Jr. et al., 2016).

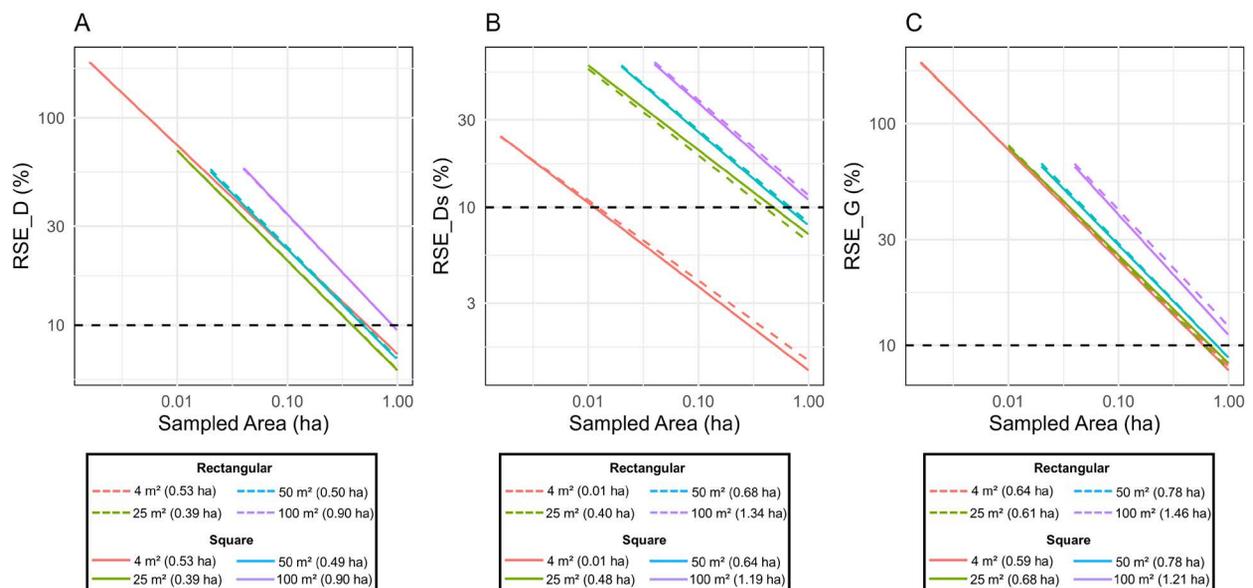


Figure 6: Relative Sampling Error (RSE) of the structural variables of the 5 cm ≤ DBH ≤ 10 cm diameter class in the 1 ha plot in relation to the sampled area. A – Tree density, B – Stem density, and C – Basal area. RSE – Relative Sampling Error, D – Tree density, D_s – Stem density, G – Basal area. The graphs are plotted on a logarithmic scale to facilitate visualization, and the horizontal black dashed line indicates a relative standard error (RSE) of 10%.

Table 2: Sampled area (ha) necessary to obtain an Relative Sampling Error (RSE) of 10% for the variables *D*, *D_s* and *G* for the diameter classes DBH < 5 cm and 5 cm ≤ DBH ≤ 10 cm.

Diameter Class	Variable	Plot Size (m ²)	Plot Shape	Sampled Area (ha)
DBH < 5 cm	D	4	Rectangular	0,16
			Square	0,16
		25	Rectangular	0,52
			Square	0,52
		50	Rectangular	0,98
			Square	0,98
	100	Rectangular	1,79	
		Square	1,79	
	D _s	4	Rectangular	0,08
			Square	0,08
		25	Rectangular	0,56
			Square	0,55
		50	Rectangular	1,01
			Square	0,98
	100	Rectangular	1,83	
		Square	1,81	
	G	4	Rectangular	0,24
			Square	0,24
25		Rectangular	0,67	
		Square	0,58	
50		Rectangular	1,01	
		Square	1,11	
100	Rectangular	1,80		
	Square	1,80		
5 cm ≤ DBH ≤ 10 cm	D	4	Rectangular	0,53
			Square	0,53
		25	Rectangular	0,39
			Square	0,39
		50	Rectangular	0,50
			Square	0,49
	100	Rectangular	0,90	
		Square	0,90	
	D _s	4	Rectangular	0,01
			Square	0,01
		25	Rectangular	0,40
			Square	0,48
		50	Rectangular	0,68
			Square	0,64
	100	Rectangular	1,34	
		Square	1,19	
	G	4	Rectangular	0,64
			Square	0,59
25		Rectangular	0,61	
		Square	0,68	
50		Rectangular	0,78	
		Square	0,78	
100	Rectangular	1,46		
	Square	1,21		

The discrepancy between the MAE and RSE results shows the difference between the accuracy and precision in forest sampling. Accuracy refers to the closeness of an estimate to the actual value, whereas precision indicates how closely a series of measurements align with their mean (Kershaw Jr. *et al.*, 2016). Sampling with smaller plots achieved a precision of 10%, covering a significantly smaller area compared to larger plots. However, owing to the strong bias in sampling *D*, *D*_s and *G*, the accuracy of the estimates varied depending on the diameter class and plot size used.

Our findings showed that, for sampling ecological variables such as richness and the Shannon–Weaver index, the 4 m² sampling plot was the most effective, regardless of plot shape or diameter class. It is important to notice that 218 trees were not identified and therefore were not included in the ecological variables analysis (Table 1). This limitation is likely due to challenges in identifying juvenile trees, including morphological plasticity between juvenile and mature trees, and the lack of field guides and botanical collections for this size class. These challenges are exacerbated when the species is rare and thus less familiar to parobotanists (Ferraz *et al.*, 2019).

The presence of unidentified trees among ecological variables primarily leads to an underestimation of forest diversity. This underestimation negatively impacts conservation policies because the actual diversity remains unknown, making it challenging to identify focal species for conservation, particularly during critical stages such as regeneration, and in monitoring forest development following disturbances (González-Oreja *et al.*, 2013; Daru *et al.*, 2024). In this case, we highlight the need to expand studies on the identification of juvenile trees and seedlings in the Amazon as an essential step in forest conservation and monitoring in the region.

For the structural variables, the square 4 m² sampling plot achieved the best accuracy when sampling the DBH < 5 cm diameter class. The rectangular 50 m² sampling plot yielded the best results for the *D*_s and *G* variables for the 5 cm ≤ DBH ≤ 10 cm diameter class, while for *D*, the best results were obtained with the 4 m² sampling plot, independent of shape. We emphasize the importance of accurate studies in forest mensuration, even in the face of difficulties in conducting a forest census, because they facilitate the development of truly effective sampling designs. Moreover, although we sampled a small area, inventorying all trees with a diameter at breast height (DBH) ≤ 10 cm required significant effort, and we believe this often-overlooked data will help improve forest regeneration assessments.

CONCLUSION

Sampling simulations highlighted the efficiency of square plots of 4 m² and rectangular plots with 50 m², particularly when several sampling units were used. These results not only validate the applicability of fixed-area sampling but also demonstrate the value of integrating spatial tools, such as GIS, for inventory optimization. This study confirms that random sampling, combined with advanced geospatial technologies and sound statistical methodologies, can yield

high-accuracy forest inventory data. Contrary to our initial hypothesis, we found that the largest sampling plot was not the most effective under all sampling conditions. This may be attributed to increased variability associated with larger plot sizes. Additionally, the influence of plot shape on accuracy depended on multiple factors, making it impossible to recommend a single plot shape for all scenarios. Lastly, the distinction between accuracy and precision was evident in our analysis, indicating that this relationship warrants further investigation in forest sampling.

ACKNOWLEDGEMENTS

This paper is a product of Vitor Mateus de Carvalho Morais's Master's thesis in forest science. The authors are grateful to the Graduate Program in Forest Sciences from the Federal Rural University of Amazon (UFRA) for the opportunity to conduct this study. We also thank the Laboratory of Mensuration and Forest Resource Management (LabFor) for their support in preparing this manuscript. This work is part of the research project "Dynamics of Urban Forests and Their Effect on the Planning of Anthropized Ecosystems in Belém and Surrounding Regions.

AUTHORSHIP CONTRIBUTION

Project Idea: FE; RGMN

Funding: FE; RGMN

Database: RGMN; FE

Processing: BBB; VMCM

Analysis: BBB; VMCM; RGMN

Writing: VMCM

Review: BBB; DVS; FE; RGMN

DATA AVAILABILITY

The datasets analyzed during the current study are available from the corresponding author upon reasonable request.

REFERENCES

- ARASA-GISBERT, R.; ARROYO-RODRÍGUEZ, V.; MEAVE, J. A. The impact of human disturbances on the regeneration layer of tropical rainforests. *Environmental Research Letters*, v. 19, n. 12, p. 123004, 2024. <https://doi.org/10.1088/1748-9326/ad95a0>.
- AUGUSTYNICZIK, A.L.D.; MACHADO, S. A.; FIGUEIREDO FILHO, A. F.; *et al.* Evaluation of plot sizes and sampling intensities in forest inventories. *Scientia Forestalis*, v. 41, n. 99, p. 361--368, 2013.
- BERNARDES-DA-SILVEIRA, A.; CARVALHO, S.P.C.; NICOLETTI, M.F.; *et al.* Impact of plot size on tropical forest structure and diversity estimation. *Revista de Biología Tropical*, v. 70, n. 1, p. 437-449, 2022. <https://doi.org/10.15517/rev.biol.trop.v70i1.48640>.
- BACARO, G.; ROCCHINI, D.; DIEKMANN, M.; *et al.* Shape matters in sampling plant diversity: Evidence from the field. *Ecological Complexity*, v. 24, p. 37-45, 2015. <https://doi.org/10.1016/j.ecocom.2015.09.003>.

- BIENG, M.A.N.; OLIVEIRA, M.S.; RODA, J.M.; et al. Relevance of secondary tropical forest for landscape restoration. *Forest Ecology and Management*, v. 493, p. 119265, 2021. <https://doi.org/10.1016/j.foreco.2021.119265>.
- BULLOCK, E.L.; WOODCOCK, C.E. Carbon loss and removal due to forest disturbance and regeneration in the Amazon. *Science of the Total Environment*, v. 764, p. 142839, 2021. <https://doi.org/10.1016/j.scitotenv.2020.142839>
- CHAZDON, R.L.; NORDEN, N.; COLWELL, R.K.; et al. Monitoring recovery of tree diversity during tropical forest restoration: lessons from long-term trajectories of natural regeneration. *Philosophical Transactions of the Royal Society B*, v. 378, n. 1867, p. 20210069, 2023. <https://doi.org/10.1098/rstb.2021.0069>.
- CHIU, C.H. Sample coverage estimation, rarefaction, and extrapolation based on sample-based abundance data. *Ecology*, v. 104, n. 8, p. e4099, 2023. <https://doi.org/10.1002/ecy.4099>.
- COLLI-SILVA, M.; PIRANI, J. R. Current knowledge of the occurrence and distribution of Sapindales in Brazil: a data synthesis from the Brazilian Flora 2020 project. *Brazilian Journal of Botany*, v. 45, n. 1, p. 223-235, 2022. <https://doi.org/10.1007/s40415-021-00739-3>.
- DARU, B.H. Predicting undetected native vascular plant diversity at a global scale. *Proceedings of the National Academy of Sciences*, v. 121, n. 34, p. e2319989121, 2024. <https://doi.org/10.1073/pnas.2319989121>.
- DRAPER, F.C.; COSTA, F.R.C.; ARELLANO, G.; et al. Amazon tree dominance across forest strata. *Nature Ecology & Evolution*, v. 5, p. 757-767, 2021. <https://doi.org/10.1038/s41559-021-01418-y>
- FERRAZ, I.D.K.; CAMARGO, J.L.C.; MESQUITA, M.R.; et al. Guide to Amazonian fruits, seeds & seedlings. Editora do INPA, 2019, 226p.
- GILES, A.L.; SCHIETTI, J.; ROSENFELD, M.F.; et al. Simple ecological indicators benchmark regeneration success of Amazonian forests. *Communications Earth & Environment*, v. 5, n. 1, p. 780, 2024. <https://doi.org/10.1038/s43247-024-01949-9>.
- GNONLONFON, I.; KAKÁI, R.G.; SALAKO, V.K.; et al. Structural analysis of regeneration in tropical dense forest: combined effect of plot and spatial distribution patterns. *Acta Botanica Gallica*, v. 162, n. 1, p. 79-87, 2015. <https://doi.org/10.1080/12538078.2014.984332>.
- GONZÁLEZ-OREJA, J.A.; GARBISU, C.; MIJANGOS, I.; MENDARTE, S.; ALBIZU, I. Reducing costs in biodiversity monitoring: Shortcuts for plant diversity in meadows as a case study. *Ecological Indicators*, v. 24, p. 96-104, 2013. <https://doi.org/10.1016/j.ecolind.2012.06.008>.
- GUZMÁN, D. de A. O Projeto Várzea: uma história relacional da ciência na Amazônia brasileira (1945–2019). 1. ed. Belém, PA: Paka-Tatu, 2022. 276 p.
- HANBURY-BROWN, A. R.; WARD, R. E.; KUEPPERS, L.M. Forest regeneration within Earth system models: current process representations and ways forward. *New Phytologist*, v. 235, n. 1, p. 20-40, 2022. <https://doi.org/10.1111/nph.18131>.
- HARRIS, L.B.; WOODALL, C.W.; D'AMATO, A.W. Increasing the utility of tree regeneration inventories: Linking seedling abundance to sapling recruitment. *Ecological Indicators*, v. 145, p. 109654, 2022. <https://doi.org/10.1016/j.ecolind.2022.109654>.
- HOUNSODE, M.T.D.; KAKÁI, R.G.; AZIHO, A.K.; et al. Efficiency of inventory plot patterns for the estimation of woody vegetation recruit density in a tropical dense forest in Benin. *African Journal of Ecology*, v. 53, p. 355-361, 2015. <https://doi.org/10.1111/aje.12194>.
- KARDGAR, N.; RAHMANI, R.; ZARE, H.; GHORBANI, S.; et al. Assessing the effect of plot size on species diversity in a mixed oriental beech forest. *Journal of Forestry Research*, v. 36, n. 1, p. 4, 2024. <https://doi.org/10.1007/s11676-024-01796-6>.
- KEELEY, J.E.; FOTHERINGHAM, C.J. Plot shape effects on plant species diversity measurements. *Journal of Vegetation Science*, v. 16, n. 2, p. 249-256, 2005. <https://doi.org/10.1111/j.1654-1103.2005.tb02362.x>.
- KERSHAW JR, J.A.; DUCEY, M. J.; BEERS, T.W.; et al. *Forest Mensuration*. Chichester: John Wiley and Sons, 2016. 633 p.
- LAURANCE, W.F.; FERREIRA, L.V.; MERONA, M.R.; et al. Influence of plot shape on estimates of tree diversity and community composition in central Amazonia. *Biotropica*, v. 30, n.4, p. 662-665, 1998. <https://doi.org/10.1111/j.1744-7429.1998.tb00106.x>.
- LISTER, A. J.; LEITES, L. P. Designing plots for precise estimation of forest attributes in landscapes and forests of varying heterogeneity. *Canadian Journal of Forest Research*, v. 51, n. 10, p. 1569-1578, 2021. <https://doi.org/10.1139/cjfr-2020-0508>.
- MUSA, M. B.; ANIK, C. S.; EMON, N. U.; et al. Optimal plot size and shape for sampling growing stocks and tree species diversity in tropical forests: Results from a forest inventory in Hazarikhil Wildlife Sanctuary of Bangladesh. *Forest Ecology and Management*, v. 585, p. 122679, 2025. <https://doi.org/10.1016/j.foreco.2025.122679>
- BRASIL NETO, A.B.; SCHWARTZ, G.; NORONHA, N.C.; et al. Natural regeneration for restoration of degraded areas after bauxite mining: A case study in the Eastern Amazon. *Ecological Engineering*, v. 171, p. 106392, 2021. <https://doi.org/10.1016/j.ecoleng.2021.106392>.
- OLIVEIRA, M.M.; HIGUCHI, N.; CELES, C.H.; et al. Size of plots and forms for forest inventory of tree species in Central Amazon. *Ciência Florestal*, v. 24, n. 3, p. 645-653, 2014. <https://go.gale.com/ps/i.do?id=GALE%7CA386744808&sid=googleScholar&v=2.1&it=r&linkaccess=abs&issn=19805098&sw=w&p=IFME&userGroupName=anon%7Fefc36a35&aty=openweb-entry>
- PAN, Y.; BIRDSEY, R. A.; PHILLIPS, O. L. et al. The enduring world forest carbon sink. *Nature*, v. 631, p. 563-569, 2024. <https://doi.org/10.1038/s41586-024-07602-x>.
- PHILLIPS, O.L. Sensing forests directly: The power of permanent plots. *Plants*, v. 12, n. 21, p. 3710, 2023. <https://doi.org/10.3390/plants12213710>.
- PINTO, L. O. R.; SOUZA, C. R.; TERRA, M. C. N. S; et al. Optimal plot size for carbon-diversity sampling in tropical vegetation. *Forest Ecology and Management*, v. 482, p. 118778, 2021. <https://doi.org/10.1016/j.foreco.2020.118778>.
- QIN, Y.; XIAO, X.; WIGNERON, J.P.; et al. Carbon loss from forest degradation exceeds that from deforestation in the Brazilian Amazon. *Nature Climate Change*, v. 11, n. 5, p. 442-448, 2021. <https://doi.org/10.1038/s41558-021-01026-5>.
- ROVEDA, M.; FIGUEIREDO FILHO, A.; PELISSARI, A. L.; et al. Spatial continuity in a mixed ombrophilous forest with different size and shape of sample units. *Cerne*, v. 22, n. 2, p. 189-196, 2016. <https://doi.org/10.1590/01047760201622022139>.
- SALAKO, V.K.; KAKÁI, ASSOGBADJO, A.E.; et al. Efficiency of inventory plot patterns in quantitative analysis of vegetation: a case study of tropical woodland and dense forest in Benin. *Southern Forests: a Journal of Forest Science*, v. 75, n. 3, p. 137-143, 2013. <https://doi.org/10.2989/20702620.2013.816232>.
- SANTOS, P.C.T.C.; VIEIRA, L.S.; VIEIRA, M.N.F. Os solos da faculdade de ciências agrárias do Pará. Belém: FCAP, 1983. (FCAP. Informe Didático; 05). 61p.
- SHACKELFORD, N.; DUDNEY, J.; STUEBER, M.M.; et al. Measuring at all scales: Sourcing data for more flexible restoration references. *Restoration Ecology*, v. 32, n. 8, p. e13541, 2024. <https://doi.org/10.1111/rec.13541>.
- SMITH, C.C.; HEALEY, J.R.; BERENQUER, E.; et al. Old-growth forest loss and secondary forest recovery across Amazonian countries. *Environmental Research Letters*, v. 16, n.8, p.085009, 2021. <http://dx.doi.org/10.1088/1748-9326/ac1701>.
- SFERLAZZA, S.; MALTESE, A.; DARDANELLI, G.; et al. Optimizing the sampling area across an old-growth forest via UAV-borne laser scanning, GNSS, and radial surveying. *ISPRS International Journal of Geo-Information*, v. 11, n. 3, p. 168, 2022. <https://doi.org/10.3390/ijgi11030168>.
- SWAINE, M.D.; WHITMORE, T.C. On the definition of ecological species groups in tropical rain forests. *Vegetatio*, v. 75, p. 81-86, 1988. <https://doi.org/10.1007/BF00044629>.
- TEREZO, E. F. de M. *Amazônia: 60 anos de pesquisas florestais*. Belém, PA: Marques Editora, 2014, 236 p.

UBIALLI, J.A.; FIGUEIREDO-FILHO, A.; MACHADO, S. A.; et al. Comparison of sampling and processes for estimating basal areas for groups of species from an ecotonal forest in the northern region of Matogrosso. *Acta Amazonica*, v. 39, n. 2, p. 305-314, 2009. <https://doi.org/10.1590/S0044-59672009000200009>.

VIEIRA, D.L.M.; RODRIGUES, S.B.; JAKOVAC, C.C.; et al. Active restoration initiates high quality forest succession in a deforested landscape in Amazonia. *Forests*, v. 12, n. 8, p. 1022, 2021. <https://doi.org/10.3390/f12081022>.

ZÉBAZÉ, D.; GOREL, A.; GILLET, J.F.; et al. Natural regeneration in tropical forests along a disturbance gradient in South-East Cameroon. *Forest Ecology and Management*, v. 547, p. 121402, 2023. <https://doi.org/10.1016/j.foreco.2023.121402>.

ZEIDE, B. Plot size optimization. *Forest Science*, v. 26, n. 2, p. 251-257, 1980. <https://doi.org/10.1093/forestscience/26.2.251>.