VARIABILITY OF FOREST STRUCTURE AS A FUNCTION OF TERRAIN TYPE FOR UPLAND AND FLOODPLAIN FORESTS OF THE MID-JURUÁ REGION: RESULTS FROM AIRBORNE LIDAR

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ABSTRACT

Canopy heights and vertical profiles were analyzed for 12 airborne lidar tracks acquired over forests of the mid-Juruá region, Brazil. Canopy height models were classified at 1m resolution as floodplain, terrace, hillslope, or interfluvial flat; floodplains were further separated according to Horton-Strahler (HS) stream order. RH95 canopy heights, and vertical profiles at 1m intervals, were aggregated to 30m scale and compared with Copernicus DEM heights, using a DEM transform, the Relative Terrain Height (RTH). Median canopy height ranged from 15.4 m for the Juruá floodplain to 25.5 m for hillslopes; maximum canopy heights varied from 37.4 m to 60.0 m. A strong correlation between RTH and median canopy height (r = 0.75) was found for the Juruá floodplain tracks. Vertical profiles of Juruá floodplain tracks showed that the height above ground of maximum returns increased monotonically with RTH height. Our results clearly show the influence of floodplain topography on forest canopy structure.

***Key words* —** Amazon, várzea, forest structure, riparian, floodplain topography.

1. INTRODUCTION

Seasonally inundated forest is estimated to constitute at least 10% of the lowland Amazon basin [1], and plot-based measurements of forest structure [2] and wood density [3] have found significant differences between Amazonian floodplain and upland forests. Regional characterization of Amazon carbon stocks should therefore incorporate an understanding of how forest structure varies between floodplains and uplands. Within uplands, the Height Above Nearest Drainage (HAND; [4]) has been used to identify topographically-related differences in soil moisture that are reflected in floristic composition [5], [6] and tree growth [7]. However, plot-based forest structure measurements are available for only about 0.001% of the total forest area of the Brazilian Amazon [8].

Airborne lidars are key tools for scaling up ground-based forest structure and biomass estimates to larger regions [9], and for validating canopy and terrain height estimates from spaceborne lidars such as GEDI [10]. INPE's Estimation of Biomass in the Amazon (EBA) project has collected extensive airborne lidar tracks in the Brazilian Amazon, sampling a diversity of terrain types [8]. Here we analyze airborne lidar data from the mid-Juruá region in order to evaluate 1) whether forest structure (canopy height and vertical distribution) varies as a function of terrain type (floodplain, terrace, interfluvial flat, hillslope); and 2) whether structure varies between and within floodplains of different Horton-Strahler stream orders.

2. MATERIAL AND METHODS

Twelve small-footprint, discrete-return airborne lidar tracks of approximately 12 km x 300 m were acquired in the mid-Juruá region (Figure 1) by the EBA project [8] during August and September 2016. The Trimble HARRIER 68i instrument was flown with an average height of 600 m and scan angle of 45°. Returns were recorded with a point density of 4 points m-2 and pulse footprint ≤30 cm; horizontal accuracy was estimated to range from 0.035 to 0.185 m, and vertical accuracy from 0.07 to 0.33 m [11]. We pre-processed the .las-formatted point clouds with LAStools (v. 200304) to generate bare-ground elevation and vegetation metrics. Noise removal was performed using function *lasnoise*, and ground returns were separated from non-ground returns with function *lasground*. Function *las2dem* was used to triangulate and rasterize ground returns with a pixel spacing of 1 m, and we used the *lascanopy* function to generate 1) a digital terrain model, 2) a canopy height model (using the RH95 metric: the height corresponding to the 95th percentile of return height relative to the ground), and 3) vertical canopy profiles at 1m intervals. The mean RH95 and percent returns at 1 m intervals, averaged over 30 m x 30 m cells, were used in the analysis. In addition, the maximum 1 m RH95 value within each 30 m x 30 m cell was examined as an indicator for large trees, which can account for a large portion of forest volume [12].

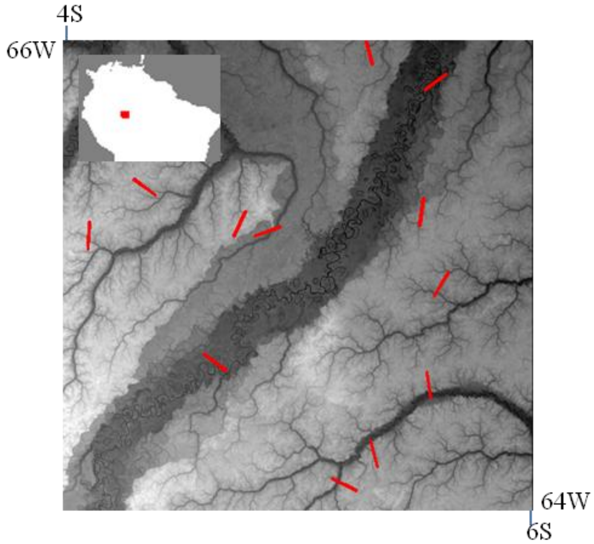

Figure 1. Lidar tracks acquired in the mid-Juruá region.

The mid-Juruá region is transected by the Juruá River, a 9th-order, meandering white-water river with headwaters in the Andean foothills and a large annual flood wave of about 14 m. The primary terrain types are river and stream floodplains, fluvial terraces, interfluvial flats, and hillslopes. The largest floodplains are the Juruá and Jutaí (9th order), and the Biá, Bóia, and Tapauá (8th order). In addition to fluvial terraces adjacent to river floodplains, a very large terrace extends northwest from the current Juruá floodplain to the Solimões River, which is thought to correspond to an earlier path of the Juruá [13]; we refer to this as the Juruá megaterrace (Figure 1).

In order to investigate the influence of terrain type on forest structure, lidar swaths were mapped into terrain types at 1 m resolution. Following artefact removal, lidar swath terrain types were mapped with a semi-automated, object-based approach. Horton-Strahler orders of objects classified as floodplains on lidar swaths were assigned based on stream orders calculated for the mid-Juruá region fluvial network, derived from the Copernicus GLO-30 DEM using the RiverTools software package. Finally, herbaceous vegetation and open water pixels were excluded from the analysis based on RH95 and patch size. In order to facilitate comparisons between terrain heights from regions at variable elevations, we applied a novel DEM normalization method, Relative Terrain Height (RTH), which quantifies the differences between DEM heights at multiple spatial scales.

3. RESULTS

Mean canopy height (RH95; Table 1) ranged from 15.4 m for the Juruá floodplain to 25.5 m for hillslopes. Mean heights for low- to mid-order floodplains (HS01 to HS06) clustered rather closely in the range of 21-22 m, but were

Terrain Type	No. of Samples	RH95 (m) Mean ± S.D.	RH95 (m), Max per cell
FP, HS01	99	22.1 ± 6.2	45.7
FP, HS02	307	22.1 ± 5.1	45.1
FP, HS03	450	21.7 ± 5.2	47.2
FP, HS04	295	22.2 ± 4.9	42.7
FP, HS05	868	21.1 ± 5.2	54.6
FP, HS06	484	21.7 ± 5.4	42.6
FP, HS07	685	17.5 ± 4.3	37.4
FP, HS08	495	18.0 ± 5.1	38.0
FP, HS09	5712	15.4 ± 5.1	58.6
FT, HS02	38	24.6 ± 5.6	53.2
FT, HS03	103	23.6 ± 4.9	49.8
FT, HS04	60	24.3 ± 5.1	40.0
FT, HS05	302	23.0 ± 4.6	59.6
FT, HS06	492	24.6 ± 5.5	50.8
FT, HS08	337	23.8 ± 5.7	60.0
FT, HS09	1644	20.6 ± 5.6	58.0
Megaterrace	2085	24.5 ± 5.2	49.7
Interfluv. Flat	7018	23.8 ± 4.6	57.1
Hillslope	21,743	25.5 ± 4.9	59.2

Table 1. Woody canopy height (RH95) statistics by terrain type for 12 Juruá lidar tracks, gridded at 30 m. FP = Floodplain; FT = Fluvial Terrace; HS = Horton-Strahler order. "Max per cell" is the maximum 1 m RH95 within each 30 m cell.

lower (17-18 m) for 7th- and 8th-order floodplains and even lower for the Juruá floodplain (15.4 m). RH95 was 1 to 2.5 m greater on fluvial terraces than on floodplains for low- to mid-order streams. For high-order streams (HS08 and HS09), the difference in RH95 between floodplain and fluvial terrace was much greater (5.2 to 5.8 m). RH95 for interfluvial flats and the Juruá megaterrace was similar to that of low- to mid-order fluvial terraces. The distributions of RH95 for grouped terrain types are shown in Figure 2. The percentage of RH95 values less than 20 m is lower for all floodplain groups, and particularly for the Juruá floodplain, which has a sizeable component less than 10 m. Maximum 1 m RH95 (Table 1) varied from 37.4 m to 60.0 m. Hillslopes, 9th-order floodplains, and 5th-, 8th, and 9th-order fluvial terraces all had maximum RH95 > 58 m.

The effects of floodplain topography on RH95 for the two Juruá floodplain tracks (T-521 and T-575; both include portions of fluvial terrace) were evaluated by

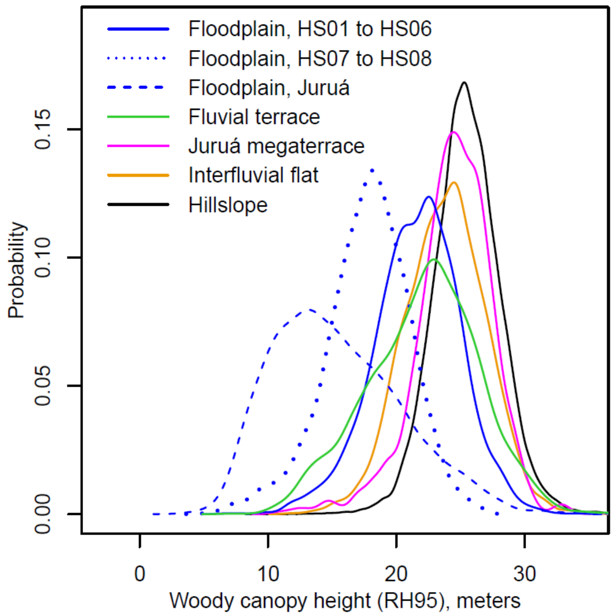

Figure 2. Canopy height (RH95) probabilities for terrain types.

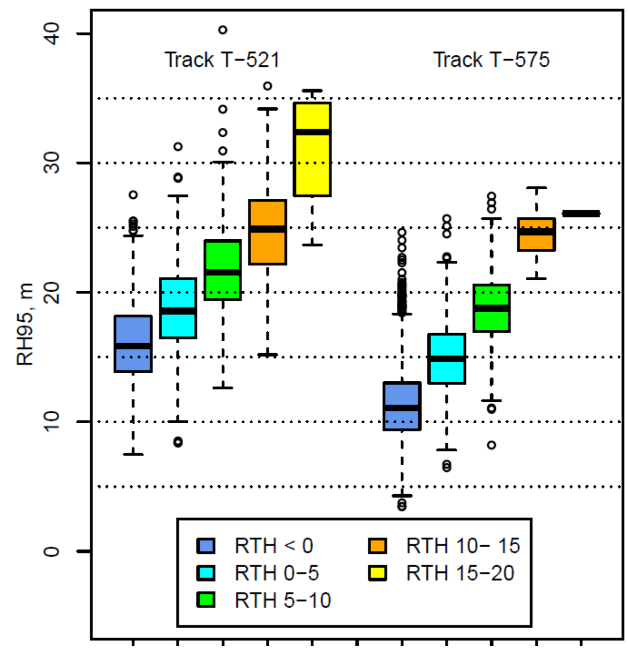

Figure 3. RH95 grouped by RTH 5-m intervals for two Juruá floodplain tracks T-521 (upstream) and T-575 (downstream)

grouping samples according to RTH. Figure 3 shows how RTH (derived from the GLO-30 DEM) normalizes the underlying elevation differences between the two tracks. For the Juruá floodplain tracks, there is a strong relationship (r = 0.75) between RTH (aggregated here at 5 m intervals) and RH95, with RH95 increasing monotonically with increasing RTH. The correlation decreases as stream order decreases, with correlations of 0.48 to 0.66 for HS06 to HS08 floodplains, and from 0.17 to 0.35 for HS01 to HS05 floodplains.

Vertical profiles of lidar returns for Juruá floodplain track T-521 show that the height above ground of maximum returns increases with RTH (Figure 4). As RTH increases from < -5 m to +15-25 m, the height of maximum returns from floodplain forest increases from < 10 m above ground to 35 m above ground. When all RTH intervals are grouped together, the Juruá floodplain and fluvial terrace display similar vertical distributions. However, looking at 5 m RTH intervals, floodplain and terrace have different distributions; for example, maximum returns for RTH of 10 to 15 m is reached at about 26 m for floodplain forest, and about 33 m for fluvial terrace forest.

4. DISCUSSION

Our results are consistent with many previous observations that floodplain forest on large Amazonian floodplains is in general shorter than terra firme (upland) forest, and that forest on levees and scroll ridges (RTH ~3-30 m) is taller than forest in swales and low-lying flats (RTH < 0 m) [14]. Lower topography is occupied primarily by shorter, successional species adapted to a prolonged flood period.

Since most previous measurements of Amazonian floodplain forest structure have focused on levees and scroll ridges (which occupy ~30% of the Juruá floodplain between 2°S and 4°S), a synthesis of plot-based meaurements to date could be biased toward taller trees. This is to our knowledge the first analysis of how Amazon floodplain forest height varies as a function of stream order. Compared with terraces, interfluvial flats, and hillslopes, mean RH95 was 2-4 m lower for HS01 to HS06 floodplains, and 8-10 m lower for HS07 to HS09. The shift in RH95 with increasing stream order parallels the increasing development of floodplain landforms, with maximum development of "negative relief" [15] in the Juruá floodplain. The lower RH95 for terraces and interfluvial flats compared with hillslopes may be related to poorer drainage on these flat terrain types. The differences in vertical canopy structure between Juruá floodplain and Juruá fluvial terrace shows the importance of landscape context: stands with RTH of 10-15 m may be regularly flooded by the annual flood pulse on the floodplain, but only sporadically flooded on the terrace.

5. CONCLUSIONS

Analysis of twelve airborne lidar tracks collected in the mid-Juruá region demonstrated the variability of forest canopy height (RH95) over different terrain types. The tallest forest was on hillslopes and terraces. Forest was 2-4 m shorter on low-order floodplains and 8-10 m shorter on the Juruá floodplain, for the sampled tracks. The airborne lidar measurements can serve to bridge the gap between field plots and spaceborne lidars such as GEDI.

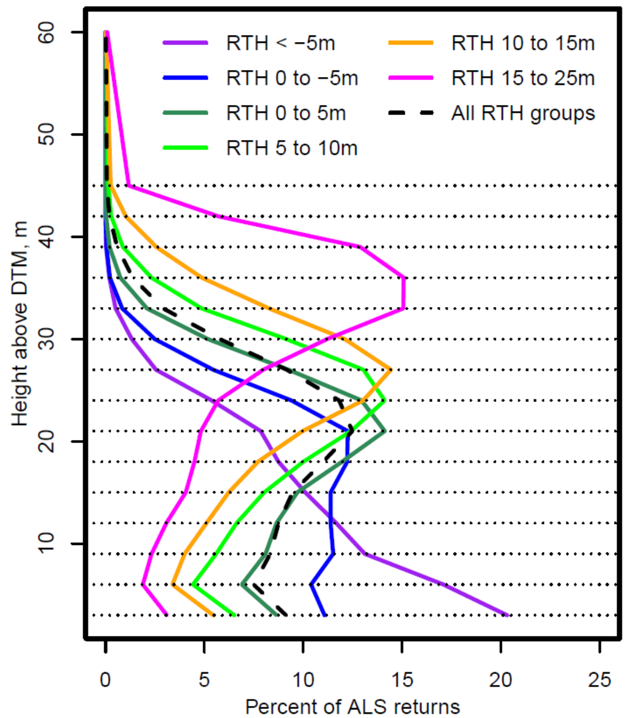

Figure 4. Vertical distribution of lidar returns above the ground at RTH 5-m intervals for a Juruá floodplain track.

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7. REFERENCES

[1] L. L. Hess, J. M. Melack, A. G. Affonso, C. Barbosa, M. Gastil-Buhl, and E. M. Novo. Wetlands of the Lowland Amazon Basin: Extent, Vegetative Cover, and Dual-season Inundated Area as Mapped with JERS-1 Synthetic Aperture Radar. *Wetlands*, v. 35: pp. 745-756, 2015.

[2] J. E. Hawes, C. A. Peres, L. B. Riley, and L. L. Hess. Landscape-scale variation in structure and biomass of Amazonian seasonally flooded and unflooded forests. *For. Ecol. Manag.*, v. 281: pp. 163-176, 2012.

[3] Y. K. Bredin, C. A. Peres, and T. Haugaasen. Forest type affects the capacity of Amazonian tree species to store carbon as woody biomass. *For. Ecol. Manag.*, v. 473: p. 118297, 2020.

[4] C. D. Rennó, A. D. Nobre, L. A. Cuartas, J. V. Soares, M. G. Hodnett, J. Tomasella, et al. HAND, a new terrain descriptor using SRTM-DEM: Mapping terra-firme rainforest environments in Amazonia. *Remote Sens. Environ.*, v. 112: pp. 3469-3481, 2008.

[5] J. Schietti, T. Emilio, C. D. Rennó, D. P. Drucker, F. R. Costa, A. Nogueira, et al. Vertical distance from drainage drives floristic composition changes in an Amazonian rainforest. *Plant Ecol. Divers.*, v. 7: pp. 241-253, 2014.

[6] M. J. Marca-Zevallos, G. M. Moulatlet, T. R. Sousa, J. Schietti, L. d. S. Coelho, J. F. Ramos, et al. Local hydrological conditions influence tree diversity and composition across the Amazon basin. *Ecography*, p. e06125, 2022.

[7] E. J. Esteban, C. V. Castilho, K. L. Melgaço, and F. R. Costa. The other side of droughts: wet extremes and topography as buffers of negative drought effects in an Amazonian forest. *New Phytol.*, v. 229: pp. 1995-2006, 2021.

[8] G. Tejada, E. B. Görgens, F. D. B. Espírito-Santo, R. Z. Cantinho, and J. P. Ometto. Evaluating spatial coverage of data on the aboveground biomass in undisturbed forests in the Brazilian Amazon. *Carbon Balance Manag.*, v. 14: pp. 1-18, 2019.

[9] M. Réjou-Méchain, N. Barbier, P. Couteron, P. Ploton, G. Vincent, M. Herold, et al. Upscaling forest biomass from field to satellite measurements: sources of errors and ways to reduce them. *Surv. Geophys.*, v. 40: pp. 881-911, 2019.

[10] F M. Urbazaev, L. L. Hess, S. Hancock, L. Y. Sato, J. P. Ometto, C. Thiel, et al. Assessment of terrain elevation estimates from ICESat-2 and GEDI spaceborne LiDAR missions across different land cover and forest types. *Science Remote Sens.*, v. 6: p. 100067, 2022.

[11] R. Dalagnol, F. H. Wagner, L. S. Galvão, A. S. Streher, O. L. Phillips, E. Gloor, et al. Large-scale variations in the dynamics of Amazon forest canopy gaps from airborne lidar data and opportunities for tree mortality estimates. *Sci. Rep.*, v. 11: pp. 1-14, 2021.

[12] V. Meyer, S. Saatchi, D. B. Clark, M. Keller, G. Vincent, A. Ferraz, et al. Canopy area of large trees explains aboveground biomass variations across neotropical forest landscapes. *Biogeosciences*, v. 15: pp. 3377-3390, 2018.

[13] D. F. Rossetti, D. L. Vasconcelos, M. M. Valeriano, and F. H. Bezerra. Tectonics and drainage development in central Amazonia: The Juruá River. *Catena*, v. 206: p. 105560, 2021.

[14] R. L. de Assis, F. Wittmann, Y. K. Bredin, J. Schöngart, C. A. N. Quesada, M. T. F. Piedade, et al. Above-ground woody biomass distribution in Amazonian floodplain forests: Effects of hydroperiod and substrate properties. *Forest Ecol. Manag.*, v. 432: pp. 365-375, 2019.

[15] J. Lewin and P. J. Ashworth. The negative relief of large river floodplains. *Earth Sci. Rev.*, v. 129: pp. 1-23, 2014.