# Forest structure gradient along a Central Amazon catena revealed by ground LiDAR

Diogo Martins Rosa [1]
Bruce Walker Nelson [1]
Dalton Freitas do Valle [1]
Juliana Schietti de Almeida [1]
Danilo Roberti Alves de Almeida [2]
Scott Christopher Stark [3]
Scott Reid Saleska [4]
Michael Lefsky [5]

[1] Brazil´s National Institute for Amazon Research - INPA
Av. André Araújo, 2.936 - Petrópolis - 69067-375 - Manaus - AM - Brazil
{mrosa.diogo, bnelsonbr, daltonvalle, jujuschietti}@gmail.com

[2] University of São Paulo - USP/ESALQ
Caixa Postal 96 - 13416-000 - Piracicaba - SP - Brazil
daniloflorestas@gmail.com

[3] Michigan State University - Department of Forestry,
East Lansing - MI - 48824 - USA
scott.c.stark@gmail.com

[4] The University of Arizona
Tucson – AZ – USA
saleska@email.arizona.edu

[5] Colorado State University
Fort Collins – CO – USA
Michael.Lefsky@colostate.edu

**Abstract.** We used an upward-looking rangefinder-type ground LiDAR to describe differences in structure between Central Amazon *terra firme* forest types along a topographic/soil gradient. The LiDAR recorded 1000 last-return distances from the ground per second. At a constant walking speed, we sampled six 150m transects per forest type. All were located in the footprint of the LBA micromet tower near Manaus. For each forest type along the gradient we produced (1) a vertical profile of leaf area density (LAD); (2) a frequency histogram of top-of-canopy (TOC) heights at 1m horizontal scale; and (3) a variogram of these fine-scale TOC heights. LAD profiles and TOC histograms show that topography imposes a gradient in canopy height and in the variance of this height. Low-lying riparian and *campinarana* forests on white sand have a lower and more homogenous canopy surface. Upper slope and plateau forests on well-drained clay and loam have a taller and more irregular canopy surface. Differences between the two topographic extremes were confirmed using a Canopy Height Model from airborne LiDAR. Autocorrelation of ground LiDAR TOC heights reached 40-100m horizontal distance in upper slope and plateau forests, but extended to less than 20m in the sandy lower slope and riparian forests. The long reach of spatial autocorrelation on upper slopes and plateaus may result from (1) a matrix of lower crowns between scattered emergents, (2) larger gaps caused by fallen emergents, and (3) broad crowns of live emergents.

**Keywords:** Tropical forest canopy, leaf area density, topographic gradient.

## 1. Introduction

In the Central Amazon eluviation of clays on incipient slopes has produced a chemically dissected landscape (Chauvel et al., 1987; Nobre et al., 2011). Plateaus with well-drained soils rich in kaolin clay grade to silty loam on steep upper slopes, to increasingly sandy soil on gentle slopes, and culminate in sandy, seasonally waterlogged valley floors. This strong gradient in soil texture and drainage explains at least 20% of variance in forest biomass, which is higher and concentrated in trees of larger diameter on plateaus (de Castilho et al., 2006). Topographic control over other attributes of forest structure has not been rigorously examined (but see Tota et al., 2012).

Here we employ an affordable ground-based LiDAR to describe changes in forest structure as a function of position on the hillslope soil catena. For four forest types that comprise a typical Central Amazon hillslope, we compare (1) vertical profiles of vegetation density in the canopy, (2) mean and variance of top-of-canopy height obtained at 1m horizontal scale and (3) the horizontal spatial autocorrelation for these canopy heights. We found strong topographic control over all these structure attributes.

## 2. Methods

The footprint of the LBA ZF2 km 34 micromet tower near Manaus, in the Asu stream catchment, is occupied by a dissected landscape divided among the segments of a typical Central Amazon hillslope catena (Rennó et al., 2008) (Figure 1). To compare forest structures, a total 900m of transect for each of four catena segments were split into six samples, each 150m long. These were spread evenly over 8 $km^2$ in the tower footprint (Figure 1A, B).

Using an upward-looking rangefinder LiDAR, that provides 1000 last-return distances per second (Riegl model LD90-3100VHS-FLP, Horn, Austria), we first obtained vertical profiles of Leaf Area Density (LAD) in stacks of $1m^3$ voxels (1m along track by 1m high by ~1m across track), where the sum of all LADs in a stack is the local LAI. Inferred LAD increases exponentially with the fraction

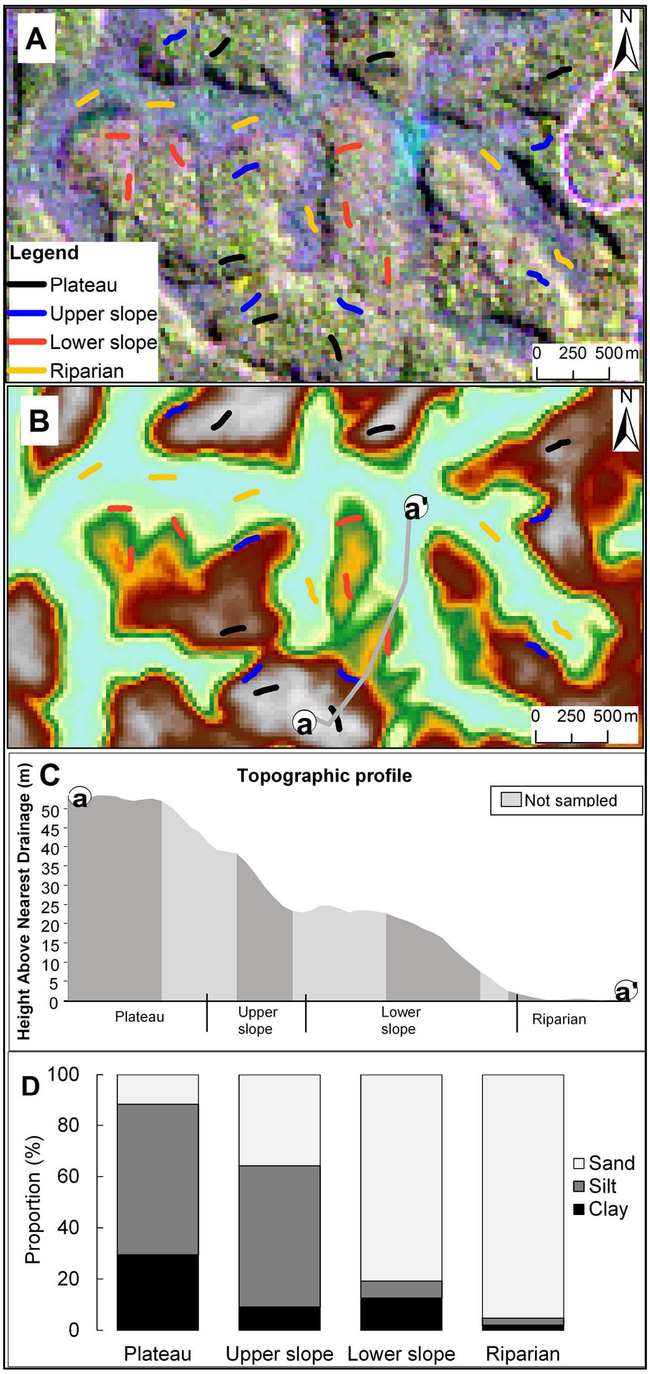


**Figure 1.** Locations of canopy profiling transects, six per forest type, on a 2014 Landsat 8 image centered on the LBA tower at 2.6091ºS, 60.2093ºW (A); SRTM-based DEM, expressed as ground Height Above Nearest Drainage (HAND) (B); four topographically defined forest types along the catena profile a-a´, classified by HAND interval and maximum permitted slope (C); average sand-clay-silt fractions for soils of four forest types along the catena (D).

of LiDAR pulses entering the base of a voxel that are returned to the sensor. Formally, LAD of each voxel is given by equation 1 (Parker et al., 2004; Stark et al., 2012). D is the voxel height, so the term 1/D cancels. The calibration coefficient K has been found to be about 0.83 near Manaus in a long transect where K was adjusted to match a directly measured LAI of 5.7 (McWilliam et al., 1993), (SC Stark, unpublished data). Here we use K=1 for convenience, providing an "effective LAD" hereafter referred to simply as LAD.

$$\mathrm{LAD} = -\ln(pulses.out\ /pulses.in) \times \frac{1}{\mathrm{D}} \times \frac{1}{\mathrm{K}} \qquad \text{(eq. 1)}$$

LAD profiles (and LAI) showed very little change over the year so here we have used data from a single month, January 2016, to compare LAD profiles between the four forest types. We also compared mean and variance of the top-of-canopy (TOC) heights at 1m horizontal scale and spatial autocorrelation of TOC heights within each 150m section of continuous transect. TOC height and height variance at 1m horizontal resolution were based on the highest LiDAR return from each 1m section of transect, providing 900 values per forest type.

We used airborne LiDAR to verify some of the forest structure patterns obtained with ground LiDAR. In June of 2008 our study area was imaged with a Leica ALS70-II (Heer-Brugg, Switzerland), with a pulse frequency of 100 kHz, flown aboard a Navajo EMB 820 (Embraer) at 120-150 knots, 1000m above the ground, with maximum cross-track scan angle of $10^o$ and maximum data strip width of 425m. The ground surface elevation was subtracted from the canopy surface elevation (the latter resolved at $1m^2$) to derive a Canopy Height Model (CHM), prepared by M. Lefsky. Because ground returns were widely spaced, they provided a very coarse ground elevation model filled by interpolation. This means that the CHM is more reliable for forests on broadly flat ground. Consequently, we compared the airborne and ground LiDAR derived forest structures only for the two broadly flat extremes of the catena – riparian and plateau forests. We used 30m SRTM data obtained in 2001 to restrict the analysis to CHM cells on flat ground (slope $< 2^o$) and we used two classes of Height Above Nearest Drainage (Nobre et al., 2011) to identify areas pertaining to the two forest types. After masking recent gaps from blowdowns that occurred in 2005 and after masking bad data strips, we were left with 220,000 1x1m airborne CHM cells of riparian forest and 310,000 CHM cells of plateau forest. From these we prepared a CHM frequency histogram for each forest and obtained their mean and standard deviation as indictors of top-of-canopy height and upper canopy surface irregularity. These were compared with the ground LiDAR histogram shapes and the derived mean and variance in top-of-canopy height, obtained at the same spatial resolution.

Our final analysis was to prepare a set of six variograms for each forest type, one for each of the 150m transects of uninterrupted ground LiDAR data. Variograms show how the average difference between all pairs of top-of-canopy heights increases with horizontal distance between the pairs. The horizontal distance at which variance no longer increases defines the maximum extent of spatial autocorrelation in upper canopy heights. This permits informed inference on possible causes of forest structure changes along the catena. We used 50 lags of 2m, extending the analysis of spatial autocorrelation out to 100m distance between pairs.

## 3. Results and Discussion

Leaf areas density profiles (Figure 2) reveal a distinct topographic gradient from the plateau down to riparian zone. First, there is an increasingly evident upper canopy mode in vegetation density moving downslope. This suggests that the densely leafy upper canopy surface occupies a more predictable height toward the base of the catena, and that upper canopy surface becomes more irregular toward the plateau. Second, the understory is denser in the riparian and plateau forests, but more open in the white-sand *campinarana* forest, found on lower slopes.

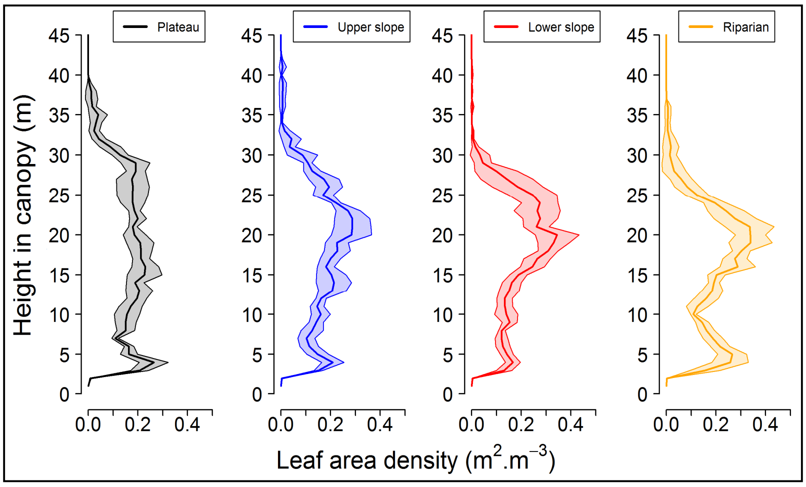


**Figure 2.** Profiles of Leaf Area Density for the four forest types, averaged for 150 values at each height. Solid lines are overall means from six replicate transects of 150m length. Shaded areas are 95% CI.

The hypothesis that LAD profiles indicate a more homogeneous upper canopy height downslope was confirmed by comparing histograms of the top-of-canopy heights obtained at 1m horizontal intervals (Figure 3). Narrow histograms indicate a more homogeneous upper canopy surface, while broader histograms indicate irregular upper surface. Riparian and *campinarana* forests clearly have smoother upper canopy surfaces of lower stature, compared with upper slope and plateau forests. Increasingly irregular canopy of greater height as one moves upward on hillslopes is also evident in a comparison of the top of canopy heights and their variances, based on the highest return from each 25m segment of transect (Figure 4).

With both airborne and ground LiDAR we found that riparian forest top-of-canopy heights had a lower mean and a smaller variance than did plateau forest, again indicating a shorter and a smoother upper canopy surface (Figure 5). The ground LiDAR detected two dominant classes of upper canopy heights in the plateau forest, one at 18-26m height and the other, at 28-32m. This was not seen in the airborne LiDAR CHM. The modal upper canopy height obtained from airborne data was about 2m shorter in riparian forest and about 4m shorter in plateau forest, compared to the ground LiDAR. In part, this may be a consequence of the dense understory in both forests occluding the ground as seen from above. But this does not explain the larger disagreement for plateau, because understory vegetation is denser in riparian forest.

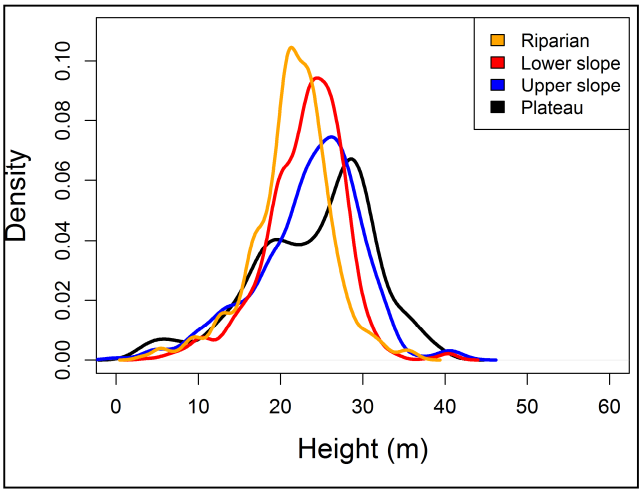


**Figure 3.** Smoothed frequency histograms of top-of-canopy heights at 1m horizontal resolution (n=900 per forest type).

ISBN: 978-85-17-00088-1

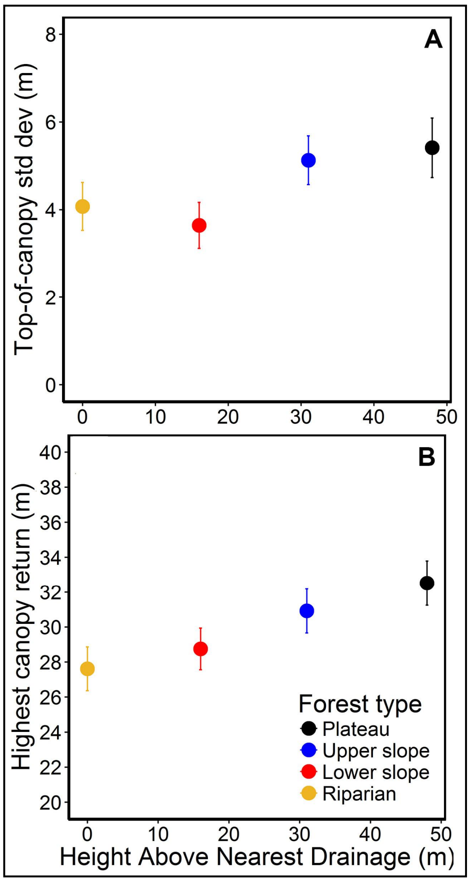


**Figure 4.** Upper slope and plateau forests have more irregular canopy surface (A) and taller trees (B), than do riparian and *campinarana* forests. Based on the highest LiDAR return from each 25m segment of transect (CI= 2SE; n=36 segments per forest type).

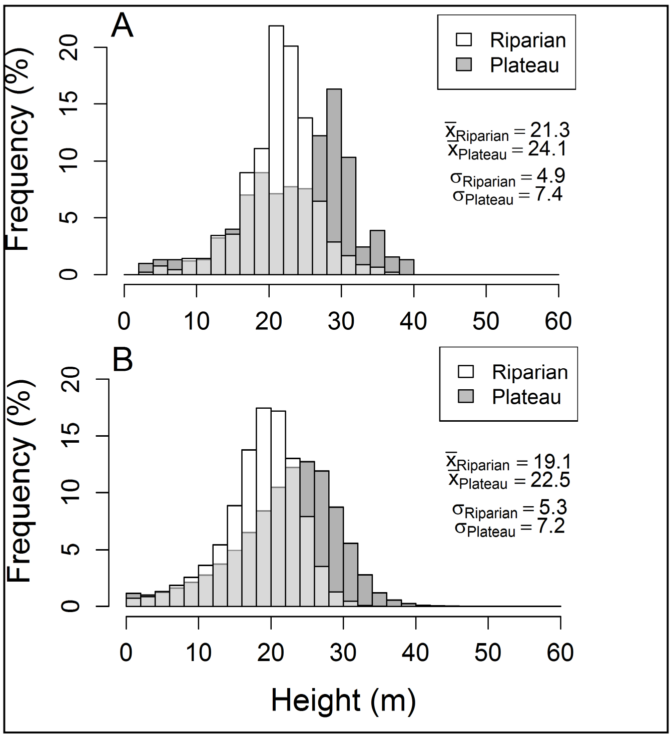


**Figure 5.** Frequency histograms of riparian and plateau forests´ top-of-canopy heights at 1m horizontal resolution, from ground LiDAR data (A) and from a Canopy Height Model derived from airborne LiDAR (B).

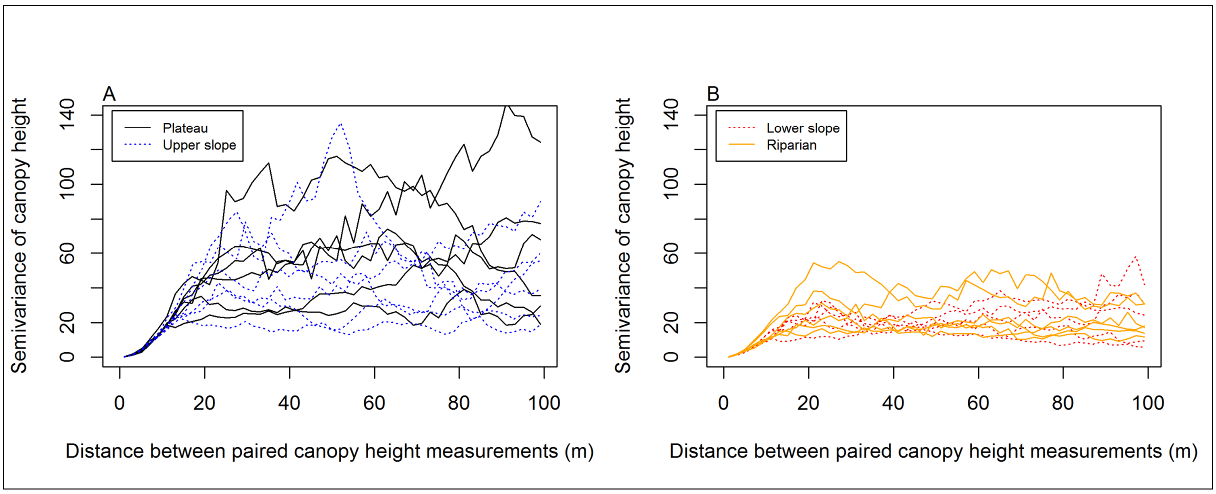


**Figure 6.** Variograms for all pairs of top-of-canopy heights using 50 lags of 2m horizontal distance, for the 150m linear transects of each forest type.

Variograms of top-of-canopy heights obtained at 1m horizontal scale (Figure 6) show that the two forests on white sand located at the lower end of the catena generally attained lower total variance than did plateau and upper slope forests, indicating once again a more homogeneous canopy surface lower down on the hillslope. There was no autocorrelation beyond 20m horizontal distance in these two lower forests (Figure 6B). Variograms for the upper slope and plateau forests were less consistent (Figure 6A). Some were like those of the lower catena forests, reaching a sill at low variance and at pair distances of less than 30m. For other transects of the upper catena forests, autocorrelation was still present at pair distances of 100m. We speculate that the longer reach of autocorrelation in these two upper catena forests is due to a matrix of lower crowns between scattered emergents, larger gaps caused by fallen emergents and broad crowns of live emergents.

## 4. Conclusions

Along a topographic gradient (soil catena) in the Central Amazon, ground LiDAR detected clear trends in top-of-canopy height, top-of-canopy smoothness and the spatial autocorrelation of top-of-canopy height.

## 5. Acknowledgements

Ground LiDAR fieldwork and data analysis were supported by the Fundação de Amparo à Pesquisa do Estado do Amazonas (FAPEAM) as part of the *Green Ocean Amazon* (GOAmazon) funding call (013/2013 - FAPEAM). The National Institute for Amazon Research (INPA) and its Large-Scale Biosphere-Atmosphere Project (LBA) maintain the study site, the micromet tower and provided logistical support. Danilo Almeida acknowledges support from São Paulo Research Foundation (FAPESP) (grant 2016/05219-9).

## References

Chauvel, A.; Lucas, Y.; Boulet, R. On the genesis of the soil mantle of the region of Manaus, Central Amazonia, Brazil. **Experientia**, v. 43, n. 3, p. 234-241, 1987.

de Castilho, C.V.; Magnusson, W.E.; de Araújo, R.N.O.; Luizao, R.C.; Luizao, F.J.; Lima, A.P.; Higuchi, N. Variation in aboveground tree live biomass in a central Amazonian forest: effects of soil and topography. **Forest Ecology and Management**, v. 234, n. 1, p. 85-96, 2006.

McWilliam, A.L.; Roberts, J.M.; Cabral, O.M.R.; Leitao, M.V.B.R.; de Costa, A.C.L.; Maitelli, G.T.; Zamparoni, C.A.G.P. Leaf area index and above-ground biomass of terra firme rain forest and adjacent clearings in Amazonia. **Functional Ecology**, v. 7, n. 3, p. 310-317, 1993.

Nobre, A.D.; Cuartas, L.A.; Hodnett, M.; Rennó, C.D.; Rodrigues, G.; Silveira, A.; ... Saleska, S. Height above the nearest drainage -- a hydrologically relevant new terrain model. **Journal of Hydrology**, v. 404, n. 1, p. 13-29, 2011.

Parker, G.G.; Harding, D.J.; Berger, M.L. A portable LIDAR system for rapid determination of forest canopy structure. **Journal of Applied Ecology**, v. 41, n. 4, p. 755-767, 2004.

Rennó, C.D.; Nobre, A.D.; Cuartas, L.A.; Soares, J. V.; Hodnett, M.G.; Tomasella, J.; & Waterloo, M.J. HAND, a new terrain descriptor using SRTM-DEM: Mapping terra-firme rainforest environments in Amazonia. **Remote Sensing of Environment**, v. 112, n. 9, p. 3469-3481, 2008.

Stark, S. C.; Leitold, V.; Wu, J. L.; Hunter, M. O.; de Castilho, C. V.; Costa, F. R.; ... Keller, M. Amazon forest carbon dynamics predicted by profiles of canopy leaf area and light environment. **Ecology Letters**, v. 15, n. 12, p. 1406-1414, 2012.

Tota, J.; Fitzjarrald, D.R.; da Silva Dias, M. A. Amazon rainforest exchange of carbon and subcanopy air flow: Manaus LBA site -- a complex terrain condition. **The Scientific World Journal**, v. 2012, p. 1-19, 2012.