Using lidar remote sensing to quantify tree-fall gaps in tropical rain forests

Fernando Del Bon Espírito-Santo [1]
Sassan Saatchi [2]
Michael Keller [3,4,5]

[1] Lancaster Environment Center
Lancaster University, LA1 4YQ, UK
f.delbon@gmail.com

[2] NASA Jet Propulsion Laboratory
California Institute of Technology, Pasadena, CA 91109, USA
Sasan.S.Saatchi@jpl.nasa.gov

[3] USDA Forest Service, International Institute of Tropical Forestry,
San Juan, Puerto Rico;
[4] Inst. for the Study of Earth, Oceans and Space,
University of New Hampshire, Durham, NH 03824, USA;
[5] EMBRAPA Informática Agropecuária CEP 13083-886 Campinas, SP, Brazil
mkeller.co2@gmail.com

Abstract. Remote observation using light detection and ranging (lidar) offers a unique opportunity to quantify the geometry and size structure of tropical forests contiguously at fine spatial resolution. We used ten samples of airborne lidar data from tropical forests – six regions from Brazil, and other Neotropical forests such as Peru, French Gui, Panama and Costa Rica. We quantify gap size frequency distribution along vertical and horizontal dimensions in ten Neotropical forest canopies distributed across gradients of climate and landscapes using airborne lidar measurements. We found that natural forest disturbances (tree-fall gaps) follow a power-law distribution. Mean gap area (50 to 900 m^2) and frequency (10,960 to 27,158) varied considerably among sites (200-ha each). However, we found that imposing a minimum gap area (20 m^2) constrained the exponent of the power-law fit of gap frequency to a narrow range from -1.2 to -1.3. This contrasts with previous studies that included smaller canopy gaps (1-20 m^2). The convergence of gap frequency distribution represented by the narrow range of the power-law exponents found in this study suggests an invariant scaling property of gaps in Neotropical forests.

Keywords: Remote Sensing, Image Processing, Lidar, Amazon and Natural Forest Disturbances.

1. Introduction

Lidar provides direct measurements of tree canopy heights (Lefsky *et al.* 1999), gap size can be detected aboveground at different heights (Kellner & Asner 2009; Asner *et al.* 2013; Boyd *et al.* 2013; Espírito-Santo *et al.* 2014a), allowing the formulation and understanding of the mechanisms of gap formation and recovery processes across the vertical dimension of forests. At horizontal scales, detailed data of forest gap size and shape, ranging from small openings (≤ 1 m^2 to a few hundreds of m^2) have been published based on detailed ground surveys (Runkle 1981; Brokaw 1982; van der Meer *et al.* 1994; Hubbell *et al.* 1999), but studies of large forest blowdowns were rare (Nelson *et al.* 1994). Lidar offers a means to explore a wider range of gap sizes (Kellner & Asner 2009; Kellner *et al.* 2011; Asner *et al.* 2013) including large forest blow-downs (several hectares) (Chambers *et al.* 2013; Espírito-Santo *et al.* 2014a) and providing the spatial data to quantify the full spectrum of disturbances from square meters to thousands of hectares (Espírito-Santo *et al.* 2014a) and successions (Chambers *et al.* 2013).

Do natural forest disturbances follow a power-law distribution? Recent studies suggest that tropical forest gap size frequency distributions follow a power law (Fisher *et al.* 2008) the form $Pr(x) \sim x^{-\lambda}$, where λ is the gap-size exponent. Much of this evidence has been gained using airborne light detection and ranging (lidar) techniques that remotely sense forest structure at high vertical and horizontal resolutions with strong sensitivity. The power-law exponent, as inferred from lidar measurements, was reported to range between -2.4 and -1.59 (Kellner & Asner 2009, Kellner *et al.* 2011, Asner *et al.* 2013, Boyd *et al.* 2013 Lobo & Dalling 2014). However, the causes of this broad variation are unclear because the empirical estimation of depends on how minimal gap size, and gap height have been defined (Parker *et al.* 2004). Here we quantify the gap size power-law exponent (λ) across a broad range of tree-dominated communities using high-resolution airborne lidar remote sensing from ten Neotropical forest sites. We test if the distribution of tree-fall gaps follow a power-law distribution using different minimum gap sizes. Quantifying the distribution of natural forest disturbances will allow us to predict natural forest mortality at large scale of tropical rain forests (Espírito-Santo *et al.* 2014a).

2. Methodology

Our study sites are located in Central and South America (Figure 1). We used ten samples of airborne lidar data from tropical forests. We included lidar data from six regions of Brazil, and other Neotropical forests such as Peru (Boyd *et al.* 2013), French Guiana (Vincent *et al.* 2012), Panama (Lobo & Dalling 2013) and Costa Rica (Kellner & Asner 2009). Sample location corresponds to a total area of 200 hectares (2 km x 1 km) of undisturbed forests each of the ten sites. Data were collected in different periods, altitudes, laser sensors and acquisition procedures. All data collections were operated by aircrafts, except for French Guiana where the acquisition was operated by a helicopter (Vincent *et al.* 2012). On average the lidar acquisition altitudes were between 1,000 and 1,600 for all sties, except for French Guiana (170 - 220 m). Regardless of those differences in lidar acquisitions, the density of lidar pulses is high for all sites (~ 4 m^{-2}).

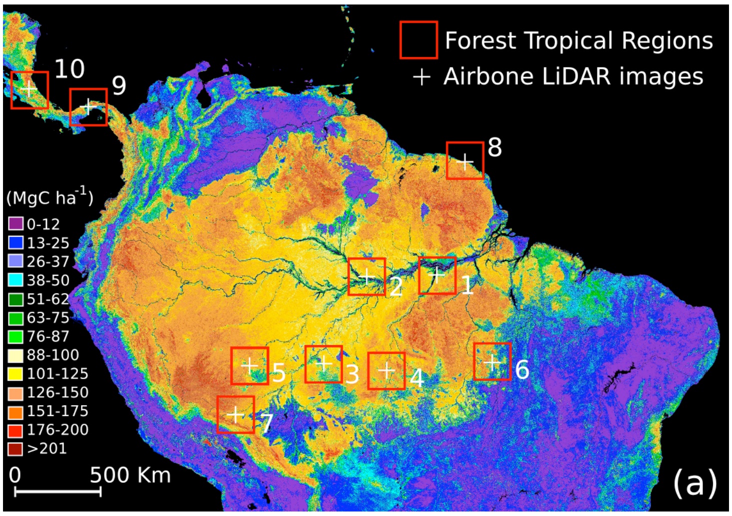

Figure 1. Spatial distribution of ten forest tropical regions of Brazil (1-Tapajós National Forest, 2-Ducke Reserve, 3-Jamari National Forest, 4-Tanguru Forest, 5-Antimary State Forest and 6-Cotriguaçu Forest), Peru (7-Tambopata National Reserve), French Guiana (8-Paracou station), Panama (9-BCI) and Costa Rica (10-La Selva) with airborne lidar remote sensing underlain by an aboveground biomass map of the Neotropical forests (Saatchi *et al.* 2011).

We used lidar data to derive canopy height models (CHM) in order to characterize and quantify forest gap sizes (Figure 2). Laser returns were used to generate a digital terrain model (DTM) and digital surface model (DSM) both at 1 m^2 pixel resolution, with the following exceptions. At Tambopata, we used existing lidar-derived DTM and DSM of 2 m^2, but we anticipate that this spatial resolution did not compromise the detection of canopy openings in Peru (Boyd *et al.* 2013). At Paracou (Vincent *et al.* 2012) and La Selva (Kellner & Asner 2009) we also used pre-processed DTM and DSM. Details of the lidar image processing for those areas are described elsewhere (Kellner &

Asner 2009; Kellner *et al.* 2009; Vincent *et al.* 2012), but briefly, laser points were processed to generate raster images (pixel resolution = 1 m) of DSM and DTM (Gatziolis & Andersen 2008). The DSM was produced by interpolations of all first return points of the cloud data, where elevation is relative to a reference ellipsoid. The DTM was created using a 30 m × 30 m filter passed over each flight block and the lowest elevation estimate in each kernel was assumed to be the ground. Lidar-derived canopy height model (CHM) was estimated as the difference between the canopy surface model and the digital terrain model (CHM = DSM-DTM).

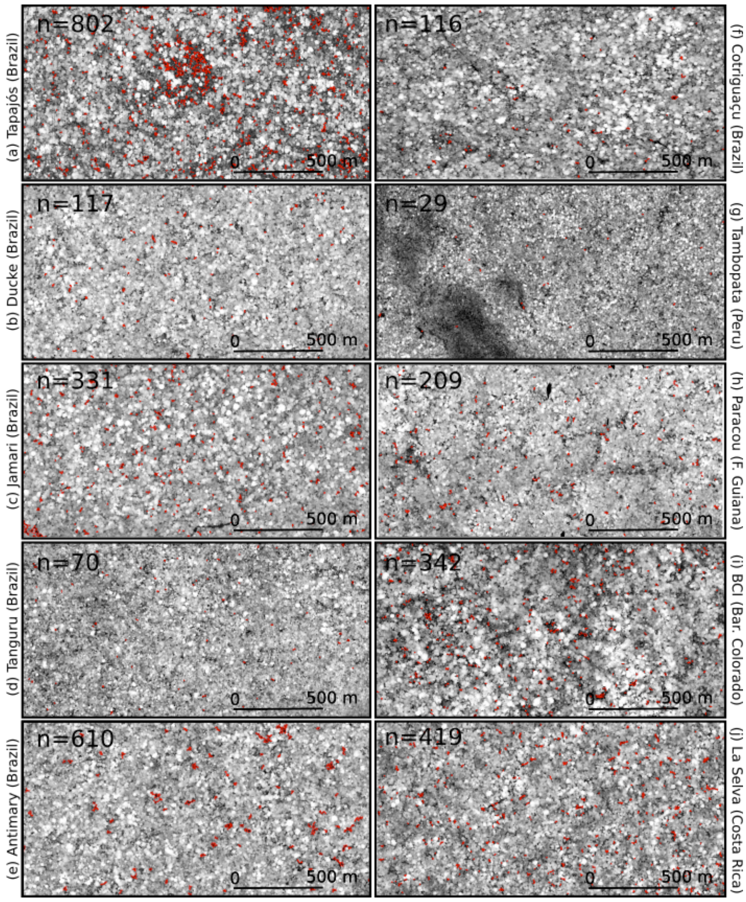

Figure 2. Tree-fall gaps at the top canopy of ten tropical forests. Spatial distributions of forest gap (x *min* ≥ 20 m^2) in 200 hectares (2 km × 1 km) overlain on a canopy height model (CHM) from airborne lidar images (spatial resolution ~1 m). Gaps were extracted from lidar CHM at 5 m aboveground using a minimum gap sizes-area threshold of the 20 m^2. Gap frequency is displayed in each site area.

3. Results and Discussion

We assessed all canopy openings related to each class of tree height, which yields a three dimensional structure of the distribution of canopy gaps (Parker *et al.* 2004). One caveat with the above definition is that all vertical holes areas retrieved by lidar CHM do not represent ground tree-falls gaps (false positives) (Lobo & Dalling 2014). Because lidar technology detects forest canopy openings of small crown space (Figure 3), we anticipate for that such small canopy openings may have another ecological meaning. We hypothesize that these canopy openings are related to sunfleck processes in forests (Chazdon & Pearcy 1991). Sunflecks are small fraction (0.5-5%) of the solar irradiance above the canopy that reaches the understory and are vital resources for light-limited understory plants (Chazdon & Pearcy

ISBN: 978-85-17-00088-1

1986). The occurrence of a sunfleck depends on (*i*) incidence of the solar path with a canopy opening; (*ii*) the movement of clouds to obscure or reveal the sun; and (*iii*) wind-induced movement of foliage and branches (Chazdon & Pearcy 1991). Considering that lidar sensors are active systems that emit pulses at very fine resolution (Lefsky *et al.* 1999), a reasonable part of the laser returns would be more related to small and temporary spaces of tree canopy than to tree-fall gaps (Runkle 1981; Brokaw 1982). We therefore called those small canopy gaps sunflecks (Chazdon & Pearcy 1986, 1991).

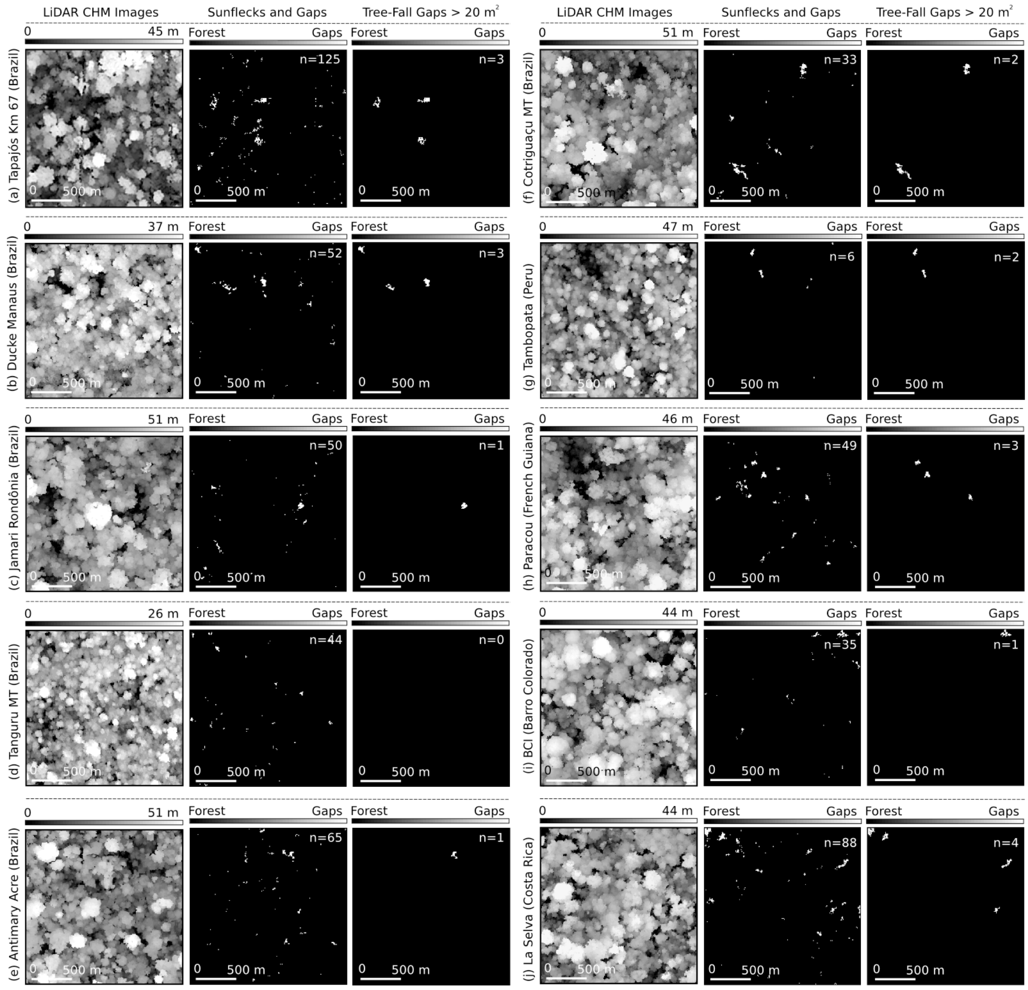

Figure 3. Forest canopy openings (sunflecks and gaps) detected by high-resolution airborne lidar data. Lidar canopy height model (CHM) and forest canopy opening sizes (white) are illustrated in 4 ha of forest samples (200 m x 200 m) of lidar CHM data from Tapajós (*a*), Ducke (*b*), Jamari (*c*), Tanguru (*d*), Antimary (*e*), Cotriguaçu (*f*), Tambopata (*g*), Paracou (*h*), BCI (*i*) and La Selva (*j*). A maximum lidar height threshold of 2 m was used to quantify threshold gaps sizes.

To understand the effects small canopy openings – the *x min* on probability density function (PDF) of forest gaps, we extracted, processed and analyzed canopy openings from two sources of data (Figure 3): (*i*) canopy opening areas ($x\ min \geq 1\ m^2$) likely related to sunfleck processes of tropical forests (Chazdon & Pearcy 1986, 1991); and (*ii*) gaps ($x\ min \geq 20\ m^2$) only from tree or branch-falls (Runkle 1981; Brokaw 1982; Hubbell *et al.* 1999; Espírito-Santo *et al.* 2014b) (Figure 4). We anticipate that the total number of small canopy

ISBN: 978-85-17-00088-1

openings ($x\ min \geq 1$ m^2) is higher than tree or branch-fall gap ($x\ min \geq 20$ m^2) disturbances (Figure 4). In 4 ha of tropical forest in Tapajós, the number of small gaps extracted from a 2-m lidar CHM is 125, but only 3 gaps exceeded 20 m^2. A recent study based on ground gap surveys of two large plots (53 and 114 ha) in Eastern Amazon (Espírito-Santo *et al.* 2014b) suggests that only 1.42 % of the low-canopy plot area are under gap processes, which indicates that the number of recent gap per ha ($\leq$1 year old) is relatively low ~ 1 or $\leq$ 1 gap ha^{-1}, with reference to Table 1 of Espírito-Santo *et al.* (2014b).

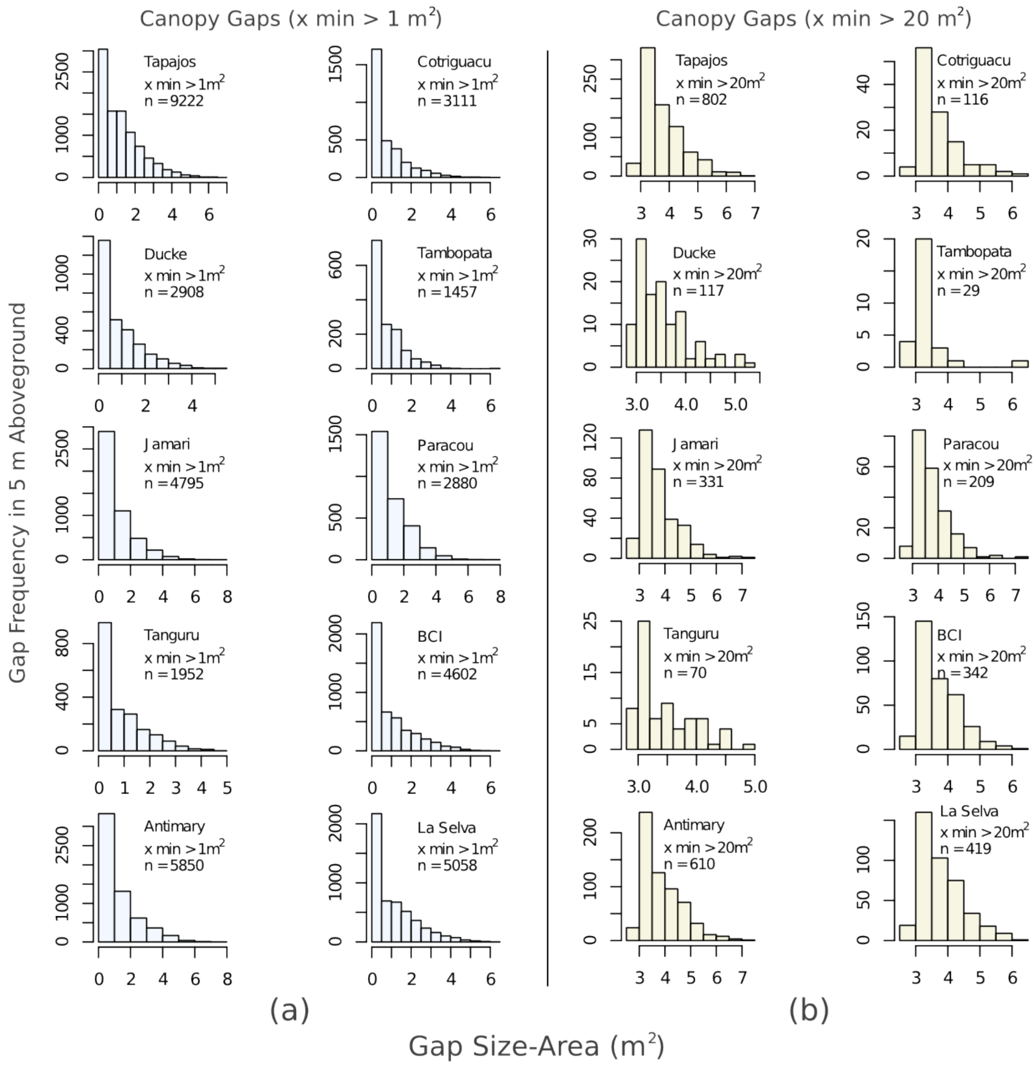

Figure 4. Frequency distribution of tree-fall gaps with minimum canopy opening area of 1 m^2 (a) and 20 m^2 (b).

Cross-site comparisons of gap size frequency distributions aboveground (from 1 to 30 m) provide the baseline to test if tree-fall gaps follow an invariant power-law scaling aboveground in tropical forests (Figure 5). We estimated the power-law exponents of the gap frequency distributions (Solé & Manrubia 1995) under the assumption that gap size follow a Pareto distribution whereby gap frequency *f(x)* is related to size-area of gaps *x*, by a function $f(x) = c\,x^{\lambda}$, where c is a constant and λ is called power-law exponent, typically negative (Solé & Manrubia 1995; White *et al.* 2008; Clauset *et al.* 2009). Because $f(x)$ is a PDF, the

ISBN: 978-85-17-00088-1

specific form of the PDF depend on whether the data are (*i*) continuous (normally bivariate power-law) or discrete (normally frequency power-law), (*ii*) on the range of $f(x)$ and (*iii*) on whether λ is < -1 or > -1 (White *et al.* 2008).

The frequency distribution of canopy openings from lidar data of the tropical forest canopy indicates that forest gap sizes follow a power-law distribution. However, the scaling exponents of gaps vary with both grain and height. Across sites, with $x\ min \geq 1\ m^2$, the exponents ranged from ~ -2.25 (forest floor) to -1.5 (top canopy). Removing small canopy openings (< 5 m^2), results in a tightly constrained range of exponents (-1.2 to -1.3) of forest gaps aboveground (Figure 5).

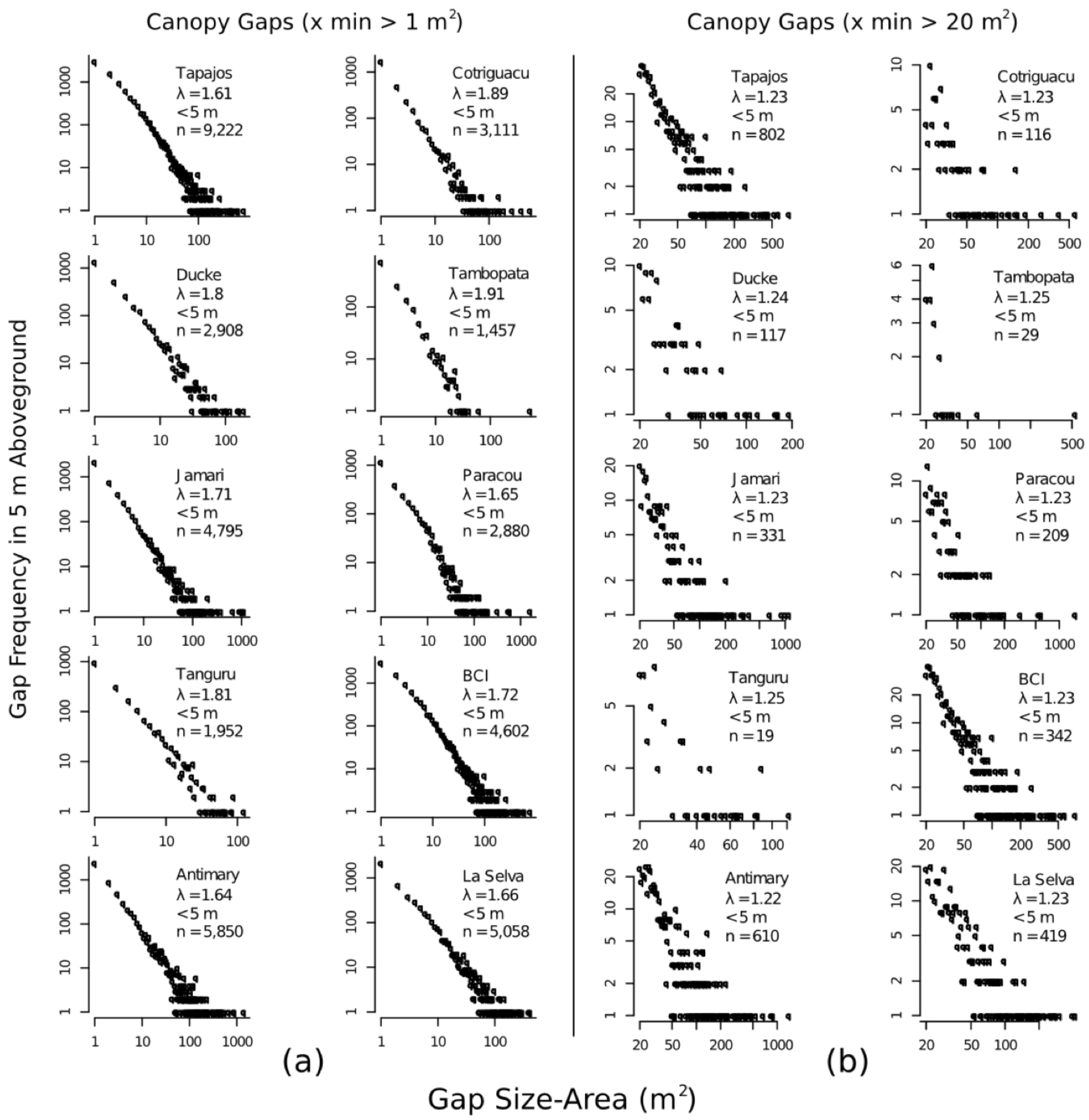

Figure 5. Comparison between gap frequency distributions of sunflecks (*a*) and tree-fall gaps (*b*) observed at 15 m aboveground in ten tropical forest regions. Sample area is 200 hectares (2 km × 100 km) of airborne lidar data (~1 m) for each forest region. Minimum gap size cut off is $x\ min \geq 1\ m^2$ for sunflecks and $x\ min \geq 20\ m^2$. Power-law exponents have negative signs.

4. Conclusions

This study showed that gap size frequency follows a power-law distribution with exponents converging across widely distributed Neotropical sites at landscape scale when a minimum gap size threshold ($x\ min > 20\ m^2$) is imposed. This invariant scaling property suggests a vertical compensation between frequency of disturbances and rate of growth and space filling. This compresses mechanisms that underlie changes on tree density (mortality and recruitment) and forest gaps (disturbance and recovery) into a relatively simple approach and highlights a way forward to predict disturbances in old growth forests by a structural canopy function – the tree size distributions expressed by forest heights. Our independent data of canopy openings shed light on the extent to which forests have experienced disturbances.

Acknowledgements

This research was supported by CalTech Postdoctoral Fellowship Program (F.E-S) at NASA-JPL. We thank the USAID, the US Department of State, the US Department of State and EMBRAPA for support of the Sustainable Landscapes Brazil program that provided lidar data from Brazilian sites.

References

Asner, G.P., Kellner, J.R., Kennedy-Bowdoin, T., Knapp, D.E., Anderson, C. & Martin, R.E. (2013). Forest canopy gap distributions in the Southern Peruvian Amazon. *PLoS One*, 8, e60875.

Boyd, D.S., Hill, R.A., Hopkinson, C. & Baker, T.R. (2013). Landscape-scale forest disturbance regimes in southern Peruvian Amazonia. *Ecol. Appl.*, 27, 1588–1602.

Brokaw, N.V.L. (1982). The definition of treefall gap and its effect on measures of forest dynamics. *Biotropica*, 14, 158–160.

Chambers, J.Q., Negron-Juarez, R.I., Marra, D.M., Di Vittorio, A., Tews, J., Roberts, D., *et al.* (2013). The steady-state mosaic of disturbance and succession across an old-growth Central Amazon forest landscape. *Proc. Natl. Acad. Sci.*, 110, 3949–3954.

Chazdon, R.L. & Pearcy, R.W. (1986). Photosynthetic responses to light variation in rain-forest species: carbon gain and photosynthetic efficiency during lightflecks. *Oecologia*, 69, 524–531.

Chazdon, R.L. & Pearcy, R.W. (1991). The importance of sunflecks for forest understory plants: photosynthetic machinery appears adapted to brief, unpredictable periods of radiation. *Bioscience*, 41, 760–766.

Clauset, A., Shalizi, C.R. & Newman, M.E.J. (2009). Power-law distributions in empirical data. *SIAM Rev.*, 706, 1–43.

Espírito-Santo, F.D.B., Gloor, M., Keller, M., Malhi, Y., Saatchi, S., Nelson, B., *et al.* (2014a). Size and frequency of natural forest disturbances and the Amazon forest carbon balance. *Nat. Commun.*, 5, 3434.

Espírito-Santo, F.D.B., Keller, M., Linder, E., Oliveira Júnior, C.R., Pereira, C. & Oliveira, C.G. (2014b). Gap formation in large forest plots of Brazilian Amazon: effects on carbon cycling and measurement using high resolution optical remote sensing. *Plant Ecol. Divers.*, 7, 305–318.

Fisher, J., Hurtt, G., Thomas, Q.R. & Chambers, J.C. (2008). Clustered disturbances lead to bias in large-scale estimates based on forest sample plots. *Ecol. Lett.*, 11, 554–563.

Gatziolis, D. & Andersen, H.-E. (2008). *A guide to lidar data acquisition and processing for the forests of the Pacific Northwest*.

Hubbell, S.P., Foster, R.B., O`Brien, S.T., Harms, K.E., Condit, R., Wechsler, B., *et al.* (1999). Light-gap disturbances,recruitment limitation, and tree diversity in a Neotropical forest. *Science*, 283, 554–557.

Kellner, J.R. & Asner, G.P. (2009). Convergent structural responses of tropical forests to diverse disturbance regimes. *Ecol. Lett.*, 12, 887–897.

Kellner, J.R., Asner, G.P., Vitousek, P.M., Tweiten, M.A., Hotchkiss, S. & Chadwick, O.A. (2011). Dependence of forest structure and dynamics on substrate age and ecosystem development. *Ecosystems*, 14, 1156–1167.

Kellner, J.R., Clark, D.B. & Hubbell, S.P. (2009). Pervasive canopy dynamics produce short-term stability in a tropical rain forest landscape. *Ecol. Lett.*, 12, 155–164.

Lefsky, M.A., Cohen, W.B., Acker, S.A., Parker, G.G., Spies, T.A. & Harding, D. (1999). Lidar remote sensing of the canopy structure and biophysical properties of Douglas-fir Western Hemlock Forests. *Remote Sens. Environ.*, 70, 339–361.

Lobo, E. & Dalling, J.W. (2013). Effects of topography, soil type and forest age on the frequency and size distribution of canopy gap disturbances in a tropical forest. *Biogeosciences Discuss.*, 10, 7103–7133.

Lobo, E. & Dalling, J.W. (2014). Spatial scale and sampling resolution affect measures of gap disturbance in a lowland tropical forest: implications for understanding forest regeneration and carbon storage. *Proc. R. Soc. B Biol. Sci.*, 281, 20133218.

van der Meer, P.J., Bongers, F., Chatrou, L. & Riera, B. (1994). Defining canopy gaps in a tropical rain-forest: effects on gap size and turnover time. *Acta Oecologica - Int. J. Ecol.*, 15, 701–714.

Nelson, B.W., Kapos, V., Adams, J.B., Oliveira, W.J., Braun, O.P.G. & Amaral, I.L. (1994). Forest disturbance by large blowdowns in the Brazilian Amazon. *Ecology*, 75, 853–858.

Parker, G.G., Harmon, M.E., Lefsky, M.A., Chen, J., Pelt, R. V, Weis, S.B., *et al.* (2004). Three-dimensional structure of an old-growth pseudotsuga-tsuga canopy and its implications for radiation balance, microclimate, and gas exchange. *Ecosystems*, 4, 440–453.

Runkle, J.R. (1981). Gap regeneration in some old-growth forests of the Eastern United States. *Ecology*, 62, 1041–1051.

Saatchi, S.S., Harris, N.L., Brown, S., Lefsky, M., Mitchard, E.T.A., Salas, W., *et al.* (2011). Benchmark map of forest carbon stocks in tropical regions across three continents. *Proc. Natl. Acad. Sci. U. S. A.*, 108, 9899–9904.

Solé, R. V & Manrubia, S.C. (1995). Are rainforests self-organized in a critical state? *J. Theor. Biol.*, 173, 31–40.

Vincent, G., Sabatier, D., Blanc, L., Chave, J., Weissenbacher, E., Pélissier, R., *et al.* (2012). Accuracy of small footprint airborne LiDAR in its predictions of tropical moist forest stand structure. *Remote Sens. Environ.*, 125, 23–33.

White, E.P., Enquist, B.J. & Green, J.L. (2008). On estimating the exponent of power-law frequency distributions. *Ecology*, 89, 905–912.