LiDAR shows that higher forests have more slender trees

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Helicopter flight above the French Guianan forest canopy.
Photograph D. Sabatier.

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RÉSUMÉ

L'IMAGERIE LiDAR MONTRE QUE LES FORÊTS LES PLUS HAUTES COMPORTENT DES TIGES PLUS ÉLANCÉES

Une opération de balayage laser aéroporté à haute densité a permis de modéliser la hauteur du couvert forestier d'un site expérimental en forêt néotropicale (à Paracou en Guyane française). La hauteur des arbres individuels a été calculée par segmentation manuelle des houppiers sur le modèle numérique de canopée et extraction de la hauteur maximale locale du couvert forestier. Trois cent quatre-vingt-seize estimations de hauteur d'arbres dominants ou émergents ont été mises en relation avec les données de terrain correspondantes pour les diamètres des tiges échantillonnées sur deux placettes de hauteur moyenne différente (28,1 m et 31,3 m). Les résultats montrent une corrélation positive et très significative entre l'élancement des tiges et la hauteur moyenne du couvert à l'échelle des placettes. La même corrélation apparaît à l'échelle des peuplements des trois essences suffisamment échantillonnées. Il est possible de conclure qu'une stratification selon la hauteur du couvert est à recommander dans le calcul de relations allométriques afin d'éviter les biais dans les estimations de biomasse aérienne.

Mots-clés : LiDAR, allométrie des arbres, fertilité, compétition, Guyane française.

ABSTRACT

LiDAR SHOWS THAT HIGHER FORESTS HAVE MORE SLENDER TREES

High-density Airborne Laser Scanning was used to derive the Canopy Height Model (CHM) of an experimental forest site in the neotropics (Paracou, French Guiana). Individual tree heights were computed by manually segmenting tree crowns on the CHM and then extracting the local maximum canopy height. Three hundred and ninety-six (396) height estimates were matched from dominant or emergent trees with the corresponding ground records of stem diameters sampled in two plots with different mean canopy heights (28.1 m vs. 31.3 m). Tree slenderness was found to be positively and very significantly correlated with mean canopy height at the plot level. The same correlation was observed at the species population level for the three species adequately sampled. It can therefore be concluded that stratification by canopy height is to be recommended when deriving allometric relationships in order to avoid bias in Above Ground Biomass estimations.

Keywords: LiDAR, tree allometry, fertility, competition, French Guiana.

RESUMEN

EL SISTEMA LiDAR MUESTRA QUE LOS BOSQUES MÁS ALTOS TIENEN ÁRBOLES MÁS ESBELTOS

Se utilizó un barrido láser aerotransportado de alta densidad para modelizar la altura del dosel de una estación experimental en un bosque neotropical (Paracou, Guayana Francesa). La altura individual de los árboles se calculó segmentando manualmente las copas en el modelo para extraer la altura máxima local del dosel. Se cotejaron trescientas noventa y seis (396) estimaciones de altura de árboles dominantes o emergentes con los correspondientes datos de campo en dos parcelas de muestreo con distinta altura promedio de dosel (28,1 m y 31,3 m). Los resultados ponen de manifiesto una correlación positiva y muy significativa entre la esbeltez de los árboles y la altura promedio del dosel a nivel de la parcela. Se observó la misma correlación a nivel de población en las tres especies suficientemente muestreadas. Puede concluirse que es aconsejable la estratificación según la altura del dosel para determinar las relaciones alométricas y así evitar sesgos en las estimaciones de biomasa aérea.

Palabras clave: LiDAR, alometría de los árboles, fertilidad, competencia, Guayana Francesa.

Introduction

In forestry and forest ecology, allometric relations have commonly been used to predict biomass from some key characteristic dimensions of trees fairly easy to measure such as stem diameter (D) and stem height (H).

However variability in H:D relationships is large both across species and across sites and robust equations are difficult to derive (BROWN, 1997; CHAVE *et al.*, 2004; KETTERINGS *et al.*, 2001; VIEILLEDENT *et al.*, 2011). Within-species variation in H:D allometry for instance is strongly related to competition and social status (FORTIN *et al.*, 2009; HARJA ASMARA *et al.*, 2012).

Community level H:D relationships in tropical forests are known to vary from site to site (CHAVE *et al.*, 2005; FELDPAUSCH *et al.*, 2010; VIEILLEDENT *et al.*, 2011). Given the high species diversity characterizing tropical forests, analysis of the variability of H:D relationships across sites has mostly been restricted to the community level (as opposed to the species level). A recent meta-analysis of a large pan tropical dataset (FELDPAUSCH *et al.*, 2010) identified climatic variables as important drivers of variation in H:D relationships. The role of vegetation structure and soil physical condition was further identified as playing a significant role, with trees in forests of high basal area or in the absence of soil physical constraints being, on average, taller at any given D. The latter finding lends support to the idea that within a particular climatic zone, site fertility will affect tree slenderness (H/D ratio).

Site fertility (as captured by height at a given age) was indeed found to be positively correlated to slenderness in plantation of *Callitris* sp. in Australia (VANCLAY & HENRY, 1988) and also in five species of mixed boreal forest covering a wide range of shade tolerance (WANG *et al.*, 1998). The generality of this relation was however questioned by Wang (GEOFF WANG, 1998), who found no such relation in his study on white spruce (*Picea glauca* Voss, a late successional species of intermediate tolerance (BURNS & HONKALA, 1990)).

The objective of the present study was therefore to answer the following questions:

Q1/ Are H:D relationships of dominant trees related to mean canopy height in old growth forest?

Q2/ Can difference in H:D allometry observed between plots be ascribed to a change in species composition or conversely does it reflect a plastic response occurring across species?

To address the points mentioned above we combined Aerial Laser Scan over the experimental station of Paracou in French Guiana, with synchronous ground inventory data and linked tree height derived from the LiDAR data and tree stem diameter measured at breast height or above buttresses.

Material & Methods

Tree Height estimate

Tree height was estimated from aerial LiDAR scans. LiDAR is an active remote sensing technology that measures distance by means of reflected laser light. In airborne laser scanning, the downward high-frequency emission of small footprint – typically dm - laser pulses from an airborne platform provides accurate data on the position of obstacles below, and a dense pattern of signal returns is obtained by the instrument's side-to-side sweep (scanning).

The Paracou experimental research station (5°15'N, 52°56'W) was set-up in the early-1980's to provide baseline information on forest recovery after forest logging activity (GOURLET-FLEURY *et al.*, 2004). A previous study (VINCENT *et al.*, 2010) established that different dominant heights and different forest structures occur on the Paracou study site in relation to soil type. We focus here on two experimental plots (P11 6.25 ha and P16 25 ha) showing significantly different mean canopy height (Wilcoxon rank sum test $P < 0.001$) of respectively 28.1 +/- 0.7 m and 31.3 +/- 0.4 m respectively (+/- Standard error of the mean canopy height at one hectare scale).

LiDAR scans were acquired in 2009 by a private contractor, Altoa (http://www.altoa.fr/) operating a helicopter-borne LiDAR. The helicopter flew at c. 170 m a.g.l. Two different systems were used at two dates 6 months apart. Each system was composed of scanning laser altimeter with a rotating mirror mechanism (Riegl LMS-Q140i-60 October or LMS-280i operated in April 2009), a GPS receiver (coupled to a second GPS receiver on the ground) and an inertial measurement unit to record pitch, roll and heading of aircraft. The laser wavelength was 0.9 m (near infrared). The scanning angle was ±30° (LMS-Q140i-60) or ±20° (LMS-280i). The laser recorded the last reflected pulse with a precision better than 0.1 m. The mean number of pulses per m^2 after combining both acquisitions was 12.4 (+/- 5.0). Mean footprint at ground level was about 45 cm (Riegl LMS-Q140i-60) or 10 cm diameter (LMS-280i).

The Canopy Height Model (CHM) was derived from the raw point cloud consisting of the pooled dataset from the two acquisitions (figure 1a). Raw data points were first processed to extract ground points using the TerraScan (TerraSolid, Helsinki) ground routine which classifies ground points by iteratively building a triangulated surface model. Ground points typically made up less than 1% of total number of return pulses. A one meter Canopy Surface Model of the area was derived by taking the local maximum height on a 1 x 1 m grid (figure 1b). Digital Terrain Model (DTM) interpolated from the ground points was subtracted from the Canopy Surface Model to obtain the CHM. Accuracy of the DTM was tested against ground-surveyed topographic data and was found to be acceptable (mean difference = 0.02 m, SD = 0.57, n = 730).

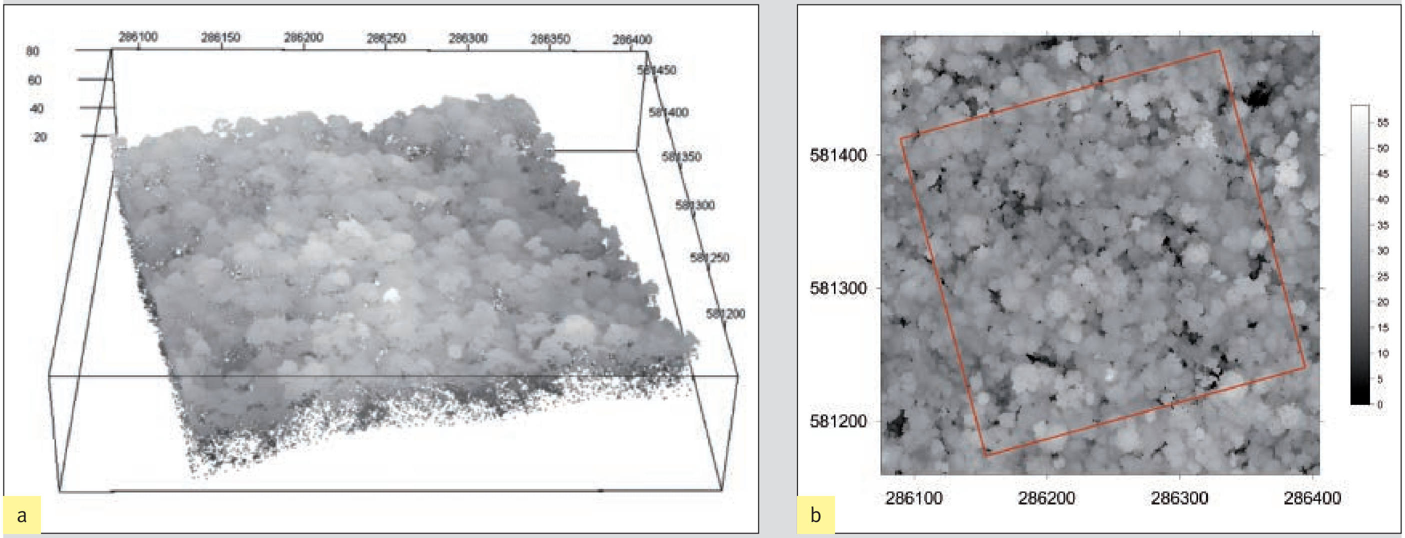

Figure 1.
(a) 3D plot of raw point cloud (Paracou Plot P11, 2009).
(b) Corresponding one-m resolution CHM (grey scale graduation in m above ground level).

The CHM was further processed with a Geographical Information System (ArcGis 9.3) to extract individual tree height. The CHM and a co-registered orthorectified aerial photograph (BD Ortho IGN, ref 973-2006-0285-0585-WGS8422N) were loaded and used to manually segment individual crowns on screen (figure 2). For a subset of trees the corresponding raw point clouds were also visualized using a dedicated software FUSION/LVD (MCGAUGHEY, 2012) to help ascertain limits between neighbouring crowns. For each delineated crown a polygonal shape file was generated which defined the area from which the local maximum was extracted and taken as the tree height.

Matching crowns with individual trees in the database was done according to tree geolocation and tree stem size (large crowns being associated with large stem diameters). Only trees for which correspondence between field inventory data could be ascertained beyond reasonable doubt were used in the present study. The total number of trees thereby selected was 396.

Adjustment of the model

A linear model was adjusted with interaction to the H:D relation at community and species scales using plot as categorical predictor and D as covariate using the lm() procedure in R (R DEVELOPMENT CORE TEAM, 2012). The linear relation was deemed adequate for the range of height explored and the associated development statuses: trees with crown fully visible from above are either co-dominant or emergent trees. The suitability of the linear model was tested be examining the residuals using the car package facilities (FOX & WEISBERG, 2011). Homoscedasticity (Breusch-Pagan) and normality of residuals (Shapiro-Wilk) tests were passed and no spurious pattern in residuals distribution detected.

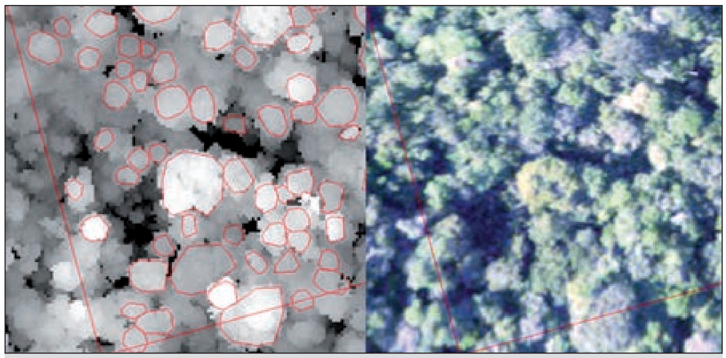

Figure 2.
Snapshot of the 2009 CHM (south-eastern corner of Plot 11) showing the digitized outlines of crown shapes (left) and the corresponding area on 2005 aerial photograph (right).

Results

At community level, plot effect was highly significant ($P<0.001$) while interaction between plot and D was not (figure 3) thus indicating that mean tree height differed systematically between plots at similar diameter. Height – at sample mean common diameter – was smaller in plot with lower canopy (Post Hoc Tuckey HSD test on least square means, $P<0.001$).

For the three species which had more than 10 individuals sampled in each plot we applied the same linear model per population of species (figure 3). In all cases mean height – at identical diameter – was significantly smaller in plot with lower canopy (Post Hoc Tuckey HSD test on least square means).

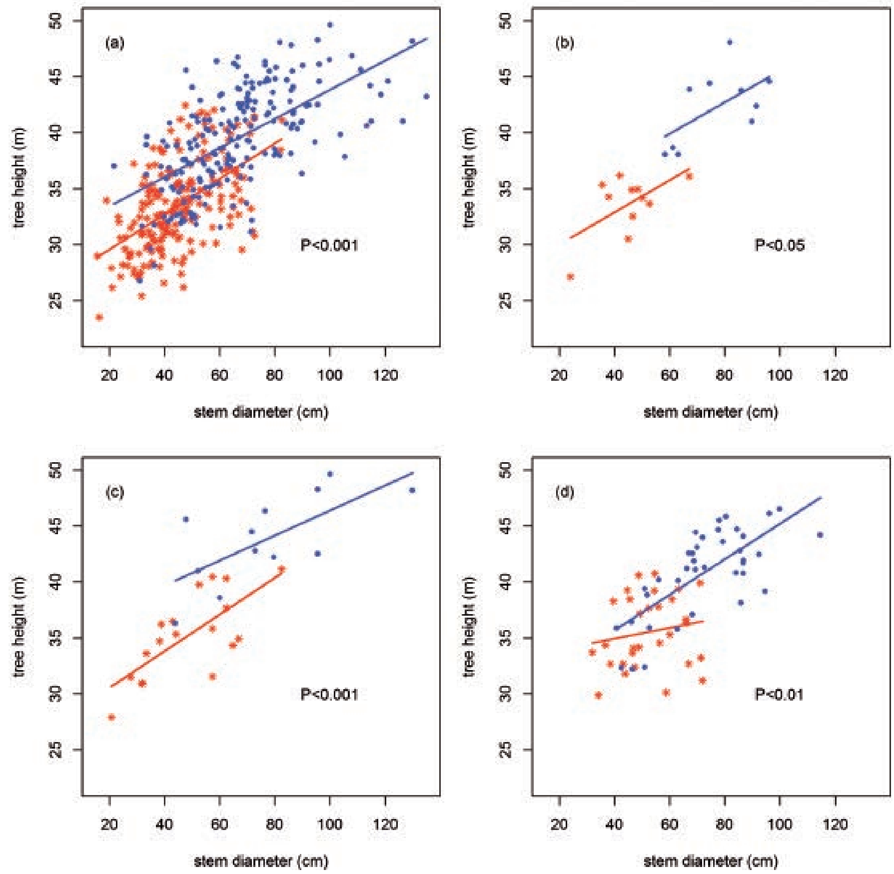

Figure 3.
H:D scatterplot and regression lines per canopy height class (dots Plot P16, stars Plot P11). (a) all species; (b) *Dicorynia guianensis;* (c) *Pradosia cochlearia*; (d) *Qualea rosea;* P values indicate probability that mean of tree height adjusted for stem diameter effect is identical across plots (Post Hoc Tuckey HSD test).

Discussion & conclusion

Within the experimental site of Paracou high canopy forest in plot P16 develops on deeper better drained soils (SCHMITT, 1984). In this plot stem density is lower and quadratic mean diameter higher than in other unlogged control plots (VINCENT *et al.*, 2010). Remarkably the mean basal area in plot P16 is not different from other plots (VINCENT *et al.*, 2010).

This study show that trees tended to be taller at similar diameter in plot P16 than in plot P11. The same trend was found at species level, for the three species well sampled on both plots (*Dicorynia guianensis* Amsh., *Cesalpiniaceae*; *Pradosia cochlearia* (Lecomte) Pennington, *Sapotaceae*; *Qualea rosea* Aublet, *Vochysiaceae*).

Those results support the hypothesis that higher forests, which develop on more fertile sites, tend to harbour more slender trees (Q1). The fact that the same trend was found for the abundant species present on both plots further indicates that the response is unlikely to be primarily related to a change in species composition but rather reflects a plastic response occurring across species (Q2).

Such an observation has practical implications for biomass estimates. Failing to adjust for change in H:D allometry associated with change in mean canopy height will lead to biased estimates of biomass. Since, as in the present case, variation in fertility can occur over small distance within a given location it is recommended that wherever possible H:D relations be derived per forest canopy height class.

Why are taller forests composed of more slender trees? It can be suggested that higher fertility induce higher growth rates both in height and in diameter which in turn induce higher competition favouring height growth over stem thickening. The mechanism may be similar to the mechanism by which at a given site (and fertility level) higher density plantations give rise to more slender trees (ZEIDE & VANDERSCHAAF, 2002). It is noteworthy that basal area in higher canopy forest in Paracou site is not significantly larger than lower canopy forest. Rather the additional Above Ground Biomass in high canopy forest is achieved entirely by way of enhanced height.

A formal explanation of the pattern described here would require a modeling framework linking explicitly fertility, competition (for light, space and belowground resources), the effect of competition at individual tree level (allocation shift between height and diameter) and the effect of competition at community level (thinning rules).

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Bibliographical references

BROWN S., 1997. Estimating Biomass and Biomass Change of Tropical Forests: a Primer. *In*: FAO Forestry Paper, FAO, Italy.

BURNS R. M., HONKALA B. H., 1990. Silvics of North America. *In:* Agriculture Handbook series. USDA Forest Service, Washington, DC.

CHAVE J., ANDALO C., BROWN S., CAIRNS M. A., CHAMBERS J. Q., EAMUS D., FOLSTER H., FROMARD F., HIGUCHI N., KIRA T., LESCURE J. P., NELSON B. W., OGAWA H., PUIG H., RIERA B., YAMAKURA T., 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia, 145 (1): 87-99.

CHAVE J., CONDIT R., AGUILAR S., HERNANDEZ A., LAO S., PEREZ R., 2004. Error Propagation and Scaling for Tropical Forest Biomass Estimates. Philosophical Transactions: Biological Sciences, 359 (1443): 409-420.

FELDPAUSCH T. R., BANIN L., PHILLIPS O. L., BAKER T. R., LEWIS S. L., QUESADA C. A., AFFUM-BAFFOE K., ARETS E. J. M. M., BERRY N. J., BIRD M., BRONDIZIO E. S., DE CAMARGO P., CHAVE J., DJAGBLETEY G., DOMINGUES T. F., DRESCHER M., FEARNSIDE P. M., FRANÇA M. B., FYLLAS N. M., LOPEZ-GONZALEZ G., HLADIK A., HIGUCHI N., HUNTER M. O., IIDA Y., ABU SILAM K., KASSIM A. R., KELLER M., KEMP J., KING D. A., LOVETT J. C., MARIMON B. S., MARIMON-JUNIOR B. H., LENZA E., MARSHALL A. R., METCALFE D. J., MITCHARD E. T. A., MORAN E. F., NELSON B. W., NILUS R., NOGUEIRA E. M., PALACE M., PATIÑO S., PEH K. S.-H., RAVENTOS M. T., REITSMA J. M., SAIZ G., SCHRODT F., SONKÉ B., TAEDOUMG H. E., TAN S., WHITE L., WÖLL H., LLOYD J., 2010. Height-diameter allometry of tropical forest trees. Biogeosciences Discuss., 7: 7727-7793. http://www.biogeosciences-discuss.net

FORTIN M., BERNIER S., SAUCIER J.-P., LABBÉ F., 2009. Une relation hauteur-diamètre tenant compte de l'influence de la station et du climat pour 20 espèces commerciales du Québec. *In :* Mémoire de recherche forestière. Ministère des Ressources naturelles et de la Faune. Direction de la recherche forestière, p. 22.

FOX J., WEISBERG S., 2011. CAR: An {R} Companion to Applied Regression. *In*: Sage.

GEOFF WANG G., 1998. Is height of dominant trees at a reference diameter an adequate measure of site quality? Forest Ecology and Management, 112 (1-2): 49-54.

GOURLET-FLEURY S., GUEHL J.-M., LAROUSSINIE O., 2004. Ecology and management of a neotropical rainforest: lessons drawn from Paracou, a long-term experimental research site in French Guiana. Paris, Elsevier, 311 p.

HARJA ASMARA D., VINCENT G., MULIA R., NOORDWIJK M. V., 2012. Tree shape plasticity in relation to crown exposure. Trees-Structure and Function, 26 (4): 1275-1285. ISSN 0931-1890

KETTERINGS Q. M., COE R., VAN NOORDWIJK M., AMBAGAU Y., PALM C. A., 2001. Reducing uncertainty in the use of allometric biomass equations for predicting above-ground tree biomass in mixed secondary forests. Forest Ecology and Management, 146 (1-3): 199-209.

MCGAUGHEY R. J., 2012. FUSION/LDV: Software for LIDAR Data Analysis and Visualization. *In*: 3.01 ed. USDA Forest Services.

R DEVELOPMENT CORE TEAM, 2012. R: A Language and Environment for Statistical Computing. *In*: R Foundation for Statistical Computing, Vienna, Austria.

SCHMITT L., 1984. Recherches sylvicoles sur les peuplements naturels en forêt dense guyanaise. Phase préliminaire : localisation du dispositif expérimental. *In* : CTFT (Cirad), France, p. 38.

VANCLAY J. K., HENRY N., 1988. Assessing site productivity of indigenous cypress pine forest in southern Queensland. Commonwealth Forestry Review, 67 (1): 53-64.

VIEILLEDENT G., VAUDRY R., ANDRIAMANOHISOA S. F. D., RAKOTONARIVO S. O., RANDRIANASOLO Z. H., RAZAFINDRABE H. N., BIDAUD RAKOTOARIVONY C., EBELING J., RASAMOELINA M., 2011. A universal approach to estimate biomass and carbon stock in tropical forests using generic allometric models. Ecological Applications, 22 (2): 572-583.

VINCENT G., WEISSENBACHER E., SABATIER D., BLANC L., PROISY C., COUTERON P., 2010. Détection des variations de structure de peuplements en forêt dense tropicale humide par Lidar aéroporté (Small foot-print airborn LiDAR proves highly sensitive to changes in structure of moist tropical forest). Revue Française de Photogrammétrie et Télédétection, 191: 42-50.

WANG Y., TITUS S. J., LEMAY V. M., 1998. Relationships between tree slenderness coefficients and tree or stand characteristics for major species in boreal mixedwood forests. Canadian Journal of Forest Research, 28 (8): 1171-1183.

ZEIDE B., VANDERSCHAAF C., 2002. The Effect of Density on the Height-Diameter Relationship. *In*: Gen. Tech. Rep SRS-48. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, p. 463-466.