LiDAR shows that higher forests have more slender trees
L’IMAGERIE LiDAR MONTRÉ QUE LES FORÊTS LES PLUS HAUTES COMPORTE 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. Les mêmes conclusions ont été tirées à l’échelle de population pour les trois espèces de plus grande importance de l’étude. 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.
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; VIELLEDENT 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; VIELLEDENT 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 soil physical constraints being, on average, taller at any given D. The latter finding lends support to the idea that soil physical constraints being, on average, taller at any given D. The latter finding lends support to the idea that soil physical constraints being, on average, taller at any given D. The latter finding lends support to the idea that soil physical constraints being, on average, taller at any given D.

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’S, 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 m² after combining both acquisitions was 12.4 (+/- 5.0). Mean footprint at ground level was about 45 cm (Riegli 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).
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 relationship 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 by 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.

**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).
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


