# Linking Remote-Sensing Information Tropical Forest Structure Crucial Role Modelling

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*A researcher is shown climbing into the canopy of a primary forest in Southern Cameroon to measure tree height and crown dimensions. Photo: Courtesy of authors.*

**Abstract**

Using remote sensing to provide reliable information over extensive areas of dense and heterogeneous tropical forests is a challenging task. Not only is the task challenging, but it also has become closely related to global concerns about reducing greenhouse gas emissions from deforestation and forest degradation, also known as the REDD process. The AMAP laboratory in Montpellier, France, is contributing to this challenge at the interface between signal processing and plant and vegetation modelling which is its central domain of expertise. Models of forest structure are an important tool to fill the scale gap between field observations and remotely sensed information. They help also to understand the complex interactions between signal and forest vegetation. As remotely-sensed data are diversifying, coupling forest structure and radiative transfer models helps to translate signal information into biophysical parameters. Refining such an approach is needed to design replicable methods that address the most challenging aspect of monitoring spatiotemporal variations of stand structure in forest types retaining high aboveground biomass.

**1. Introduction**

The forest structure is the 3D arrangement of its various constituents, namely trees of different sizes, along with their organs, such as leaves, twigs, branches and trunks. Forest structure has a strong influence on ecosystem functions, as well as on the interaction between forest ecosystems and the cycles of water, nutrients and carbon (Shugart et al. 2010). Structure has longlasting, slowly changing components like trunks and limbs, and more labile and fast-changing aspects linked to foliage and twigs. The dominant patterns of leaf shedding over seasons and years, referred to as phenology, have profound implications on ecosystem functions, and have been commonly used as a basis for devising forest typologies. Lastly, forest structure also is a determinant of the habitat of plant and animal species.

Foresters have long monitored forest structure through variables measurable from the ground, including tree trunk diameters, also called ‘diameter at breast height’ or DBH, and less systematically, tree height or derived stand characteristics as Lorey’s, or dominant height. It is standard forestry practice to use trunk diameter, alone or in conjunction with tree height, to estimate merchantable wood volumes or biomass by way of allometric relationships. Sampling through field plots or forest inventories allow foresters to estimate timber stocks and biomass over large territories at an affordable cost. However, representation on a local scale is weak in forest inventories when the sampling rate is low and information on phenology is beyond the scope of those operations. Also, since National Forest Inventory programs (McRoberts and Tomppo 2007) are still awaited in most tropical countries, revisiting forests through time to estimate growth and demography remains restricted to a limited number of permanent plots of questionable representativeness. Considering the vast extent and the often-poor accessibility of forestlands, remote sensing is seen as a potential basis for cost-effective solutions to monitor forest structure over large areas. Reducing greenhouse gas emissions from deforestation and forest degradation, so-called REDD initiatives, UNFCCC 2009, has made research in this domain particularly timely with respect to global concerns on climate change mitigation (IPCC 2007; Maniatis and Mollicone 2010). Still, applications of spatial observations of closed-canopy, high-biomass forests have so far been hindered by the saturation of most physical signals at intermediate levels of biomass or leaf cover which is classically measured in broadleaf canopies through the cumulated one sided green leaf area per unit ground area, or the leaf area index or LAI. For instance, radar signals are known to saturate for above-ground biomass (AGB) values of ca. 150 tons of dry matter per ha (Mg DM.ha-1, for L-band) while P-band data, which is not yet available from satellite-borne sensors, tend to level off above 200 Mg DM.ha-1 (Mougin et al. 1999; Le Toan et al. 2011). Vegetation indices derived from optical multispectral imagery tend to saturate above LAI values as low as 3 (Huete et al. 2002; Foody 2003), while maximum values can reach eight to 10 according to forest type, season and measurement method (e.g. Asner et al. 2003).

Signal saturation is among the main reasons explaining why AGB still resists broad scale assessment and mapping through remote sensing techniques. However, the diversification of the sources of remote-sensing information offers new prospects. Optical space-borne sensors now provide both very-high spatial resolution, or VHSR, imagery (pixels of 1-m or less) and very high temporal frequency of medium spatial resolution (e.g. pixels of 250-m with the Moderate Resolution Imaging Spectroradiometer, MODIS). Airborne small footprint light detection and ranging (LiDAR) lasers, though still insufficiently available over the tropics, provide altimetric information relating to both terrain and canopy.

It is increasingly acknowledged that a relevant use of those complementary and burgeoning techniques could be the source of major progresses regarding structure characterization and biomass assessment for dense and heterogeneous tropical forests. However, several gaps remain to be filled between classical field measurements and space-borne information, in terms of scale and accessible variables Significant steps toward this aim would require an increasing effort in modelling 3D forest structures to obtain reference mock-ups of tree stands for which the main structure variables are known. Applying radiative transfer models to these mock-ups enable the generation of signal records, for instance optical images, and the test of their potential to recover structure variables.

As a laboratory dedicated to plant and vegetation analysis and modelling, the AMAP, or “ BotAnique et bioinforMatique de l’Architecture des Plantes” or Botany and computational plant architecture, in Montpellier, France, is developing studies at the interface between stand structure modelling and image processing with a special emphasis on tropical forests.

**2. The AMAP lab**

AMAP is a joint laboratory co-operated by the University of Montpellier II, along with four French research agencies including CIRAD, CNRS, INRA and IRD. AMAP focuses on plants and vegetation, and specifically develops research at the interface between applied mathematics and informatics and plant and vegetation sciences. These investigations apply computational techniques to explore and revisit characteristics and diversity of plant taxa, evolution of functional architecture, plant-plant interactions, and stands and crops dynamics under various conditions of environmental forcing. The lab has a longstanding experience in analyzing and coding plant architecture, which includes structure, along with the dynamical processes of plant growth and morphogenesis. Such an experience is coupled with biomathematics to design and master analytical models of plant function and growth. And, with applied informatics for efficient simulations and realistic 3D visualization of structural and functional information at plant, stand and landscape scales. The lab is also involved in many projects relating to applications of image analysis at scales ranging from plant cells to space-borne vegetation or landscape observations. The combined mastering of techniques of both image analysis and plant structure modelling is an asset to take on the challenge of interfacing field knowledge on complex, heterogeneous tropical forests and broad scale remote-sensing information of increasing potential and availability. For this, AMAP can rely on its presence and partnerships in several tropical locations in French Guiana, Central Africa and Southern India.

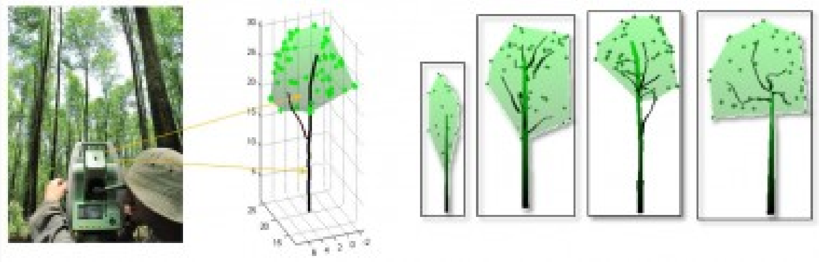

*Figure 1: Tacheometer-based measurement of tree shape and crown structure (limbs) in a mangrove forest of French Guiana. Right: “Library” of tree shapes. Photos courtesy of authors.*

**From field measurements to 3D forest models**

The challenge for mapping forest biomass or forest degradation is not only a matter of spatial technology and methods, but also depends heavily on our ability to better understand vegetation-induced signal scattering mechanisms, typically within cubic elements or voxels of 1-m3. This challenge rests on our ability to describe the distribution of forest components within the 3D space. Large-scale forest inventories generally provide DBH measurements in reference plots and, at best, X, Y positioning of trees therein. Characterizing the 3D structure implies difficult and expensive additional measurements at the scale of individual trees for tree height, trunk and branch volumes, either destructive or not, which are not affordable at stand scale, typically of 1-ha. Therefore, intensive measurements are extrapolated through modelling as to yield reference stands of explicit 3D structure that can be further used to study signal interactions with vegetation.

We develop methods to sample reference trees according to their size and status of dominant, co-dominant or dominated, from non-destructive measurements using ground-based devices such as tachometers or terrestrial lasers (Fig. 1) or even tree climbing for measurement of leaf spectral properties, crown structure or wood density at different heights. The aim is to produce a “library” of tree shapes and to improve allometric relationships predicting biomass and tree height or crown width from the easy to measure DBH. Reference stands (Fig. 2) in 3D mockups can then be built by directly applying allometric relationships to extensive forest inventory data in a kind of fast-track approach, or by using the tree shape library to “plant” virtual trees and let them adjust to their neighbors by way of a 3D-explicit stand dynamics model as STRETCH (Vincent and Harja 2008). Those mock-ups are then used as inputs for radiative transfer models and the generated signal can be analyzed and compared to real-world recorded analogues in order to assess the potential of model inversion to retrieve forest stand parameters. For instance, the DART model (turbid voxels; Gastellu-Etchegorry et al. 2004) has been applied to forest mock-ups to produce canopy images that have proved consistent with real-world VHSR images (Fig. 2), at least up to pixel sizes of 1-2-m (Barbier et al. 2010 and 2012). Models mimicking a small-footprint LiDAR signal interacting with trees are also available (ray-tracing technique, Leroy et al. 2009). Another huge advantage of modelling is that sensitivity studies of instrumental vs. forest structural effects can be carried out in a systematic way. However, future improvements will require testing the relevance of more detailed representations, in which the distribution of leaves and branches within crowns are accounted for, as well as the phenological or physiological state of trees. This is all the more exiting in that this objective requires using all the experience gathered in the AMAP unit for the characterization and simulation of individual plant architecture.

**Using very-high spatial resolution (VHSR) optical images to infer the forest structure from the canopy grain**

VHSR imagery, or approximately 1-m resolution, provided by satellite such as GeoEye, Ikonos, Orbview, Quickbird and, more recently, Pleiades, has become widely available at affordable costs, or even for free in certain locations via Google Earth, or free archives such as for Orbview. VHSR greatly increases the potential of texture analysis of canopy images by enabling texture information to directly reflect the contrast between sunlit and shadowed tree crowns, and provides information on the size distribution of crowns and inter-crowns gaps. Texture analysis of canopy satellite images can therefore provide an objective, semi-automatic implementation of the old technique of visual interpretation of aerial photographs that has been used in forestry since the 1950s. In fact, foresters and vegetation scientists have known for decades that canopy aspect in 2D views provides useful information on forest structure. Besides, texture analysis can also be applied to historical series of digitized aerial photographs prolonged by VHSR satellite imagery.

Our group has developed an approach of canopy texture called the FOTO, or Fourier-based textural ordination, method (Couteron et al. 2005; Proisy et al. 2007) that uses the Fourier 2D periodogram of canopy images and compares Fourier azimuthally averaged spectra of many images through principal component analysis (PCA). By images, we refer here to square or rectangular extracts of relevant size, generally around 1-ha, or an area that is increasingly used for field plots to measure AGB in the tropics. PCA axes ordinate images along coarseness-fineness gradients, sometimes also pointing out dominant periodicity, if any, that mostly agree with the visual appraisal.

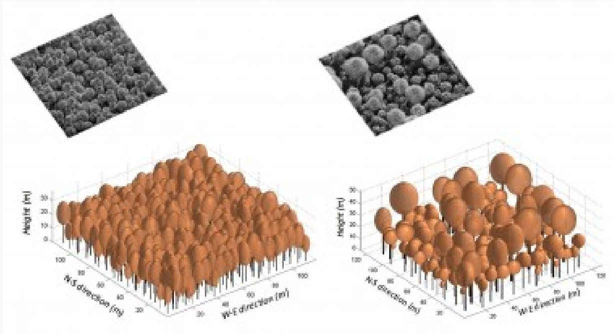


*Figure 2: 3D mockup based on field measurements carried out in two contrasted reference mangrove stands (young on the left and mature on the right). Associated simulated panchromatic canopy images (DART model) are at the top. Modified from Proisy et al. (2012).*

Case studies corresponding to particular areas, typically about 100 to 200-kilometers$^{2}$, of tropical forests have shown that scores along textural gradients generally display good correlations with the quadratic mean DBH of the stand, and more casually with stand density, and can be good predictors of AGB. Such results have been found for tropical terra firme forests in French Guiana (Couteron et al. 2005 from digitized photos) and India (Ploton et al. 2012 from Google Earth® Ikonos® images; Fig. 3), and for mangrove coastal forests in French Guiana (Proisy et al. 2007 from plain Ikonos). Contrary to pixelwise processing of either optical or radar data of high to medium spatial resolution, texture indices from VHSR images appear immune to signal saturation effects and allowed us to map AGB up to values of 500 to 600-Mg DM.ha-1 (Fig. 3). Simulated images of virtual forest stands (cf. previous section) have been used to confirm those results and understand the link between canopy texture and structure variables measurable from the ground. We then established that texture indices allow retrieving mean crown diameter, a result which has been exploited to map apparent dominant crown sizes over the whole Amazon basin (Barbier et al. 2010), and also mean quadratic DBH thanks to the allometric relationship that normally exist between tree trunk and crown (Barbier et al. 2012).

Extending those promising results to regional scales means using large arrays of images acquired under heterogeneous acquisition conditions, such as sun elevation and sun satellite angle. Since the very notion of canopy texture is linked to illumination conditions, this implies understanding the way in which acquisition parameters impact the texture indices in order to devise correction methods. We first relied on images simulated by hill shading canopy height elevation models from airborne LiDAR in a reference area in French Guiana to establish that a simple correction is possible via the concept of Bidirectional Texture Function (BTF, Barbier et al. 2011), provided that one disposes of a sufficient array of images covering the entire canopy texture gradient for all the main acquisition conditions found over a region. As this image availability condition is not yet met in the tropics, and especially over Africa, work is under way in considering the possibility of establishing a BTF from the simulation of large arrays of sufficiently realistic images.

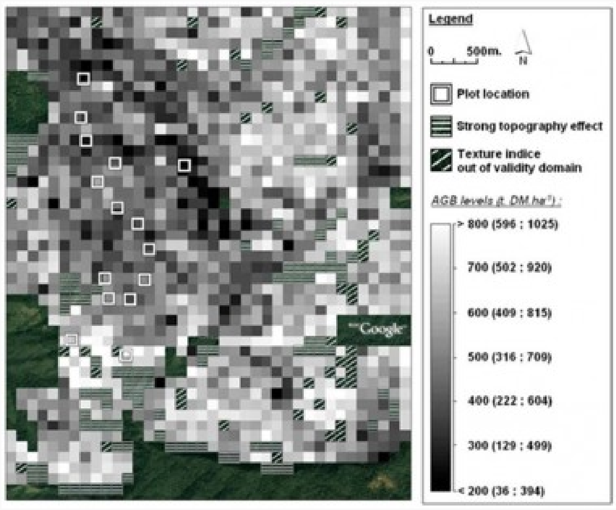


*Figure 3: Biomass map made from a Google Earth Ikonos image and the FOTO method over the mountain forests of the West coast of India (Western Ghats). Ploton et al. 2012*

**Temporal signatures of forest phenology**

Studies carried out in South America (Bradley et al. 2011) have shown the potential of multispectral data with a low spatial, yet high temporal, resolution to characterize seasonal dynamics in the canopy, and investigate possible links with environmental drivers. The interest of characterizing canopy phenology goes beyond the obvious interest for quantification of annual components in the biogeochemical cycles, as it has long been recognized that major differences in forest age, disturbance intensity, structure and dynamics were translated into the deciduousness level of the upper canopy. However although most tropical forests do seem to present some form of cyclical behavior of their reflectance, the biological mechanisms remain difficult to ascertain, as reflectance variations in a complex multi-layered canopy may result from a range of possible phenomena, although possible atmospheric perturbations of the signal that are imperfectly taken into account. The difficulty stems from the gap between what an observer can see or measure from the ground, which is very little in fact, and what is integrated within pixels of hundreds of meters or more (Fig. 4). To bridge this gap, two approaches are developed at AMAP: (i) Gathering information at multiple scales using the range of available spatial resolutions provided by space-born multispectral sensors (Fig. 4); (ii) Use of 3D models to simulate realistic canopies taking into account local observations of phenological phases.

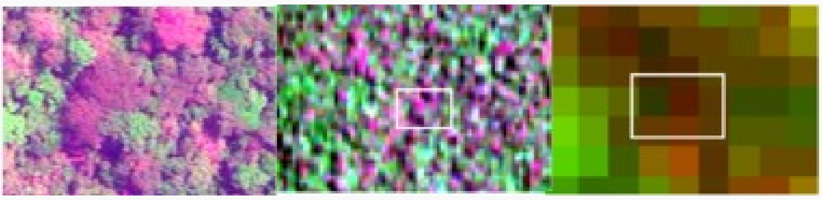

*Figure 4: Upscaling through decreasing spatial resolution from GeoEye (left) to MODIS (right) via Spot5 in a mixed deciduous-evergreen forest in Southern Cameroon. (Each frame corresponds to the leftward image.) The large emergent deciduous trees (with 'pinkish crowns' in false colours) are no longer directly detectable on MODIS.*

**From small-footprint LiDAR canopy altimetry to stand structure**

Airborne Laser systems were developed more than 20 years ago for terrain mapping. Downwards high frequency emissions of laser pulses from an airborne platform provide accurate positioning of obstacles below and a dense pattern of signal returns is accomplished by the side-to-side sweep of the instrument. From the raw 3D point cloud a forest canopy height model (CHM) is computed by subtracting from the raw point cloud an estimate of a digital terrain model (DTM) calculated from the ground points and further building a surface model from the locally highest vegetation points. CHM local statistics, first and foremost the mean canopy height, have been shown to be good predictors of stand structural variables such as basal area –- the sum of stems cross sectional area measured at breast height per ha – itself a classical predictor of AGB – with a typical residual error of about 10 percent at the 1-ha scale (Vincent et al. 2012, under revision). However, the relationship linking CHM to AGB is likely to be specific to forest types and should not be extrapolated without caution and sufficient reference ground estimates of AGB. Stratification into homogenous forest types prior to developing regressions based on CHM statistics not only helps guard against biased predictions when scaling up from plot to landscape, but may also significantly increase model precision in the future. Repeated LiDAR surveys over the same areas open-up the exciting opportunity of achieving accurate mapping of carbon fluxes, both losses and gains, over time and holds great potential for early evaluation of the impact of climate change on forest dynamics.

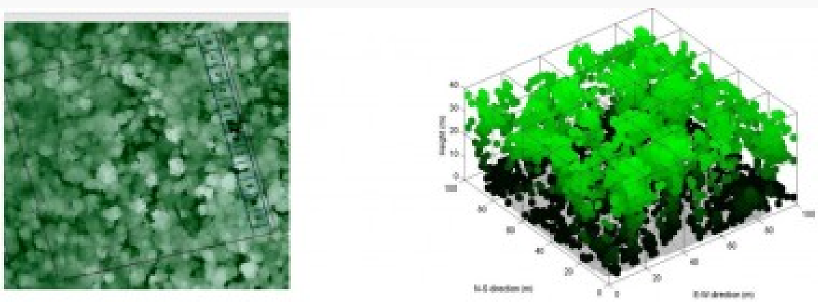

*Figure 5: Use of airborne LiDAR in French Guiana. Left: Canopy height model of a terra firme forest (D. Sabatier unpubl. report). Right: 3D LiDAR-based voxel reconstruction of an even-aged mangrove stand*

**Prospects and challenges**

The complexity and the diversity of tropical forests raise a major challenge for remote-sensing to characterize the spatio-temporal variation of stand structure and biomass in forest situations retaining either a fairly closed canopy, or AGB of medium to high values. Although convincing, broad-scale applications of medium to high spatial resolution optical imagery do exist regarding the mapping of forest vs. non-forest areas, validating methods of broad applicability for monitoring forest degradation and, or mapping biomass of dense forests has remained so far elusive (DeFries et al. 2007).

Each type of remotely sensed data displays limitations, either due to the insufficient availability or excessive cost of either the data or of the processing, as for most airborne products or space-borne VHSR imagery, or to the characteristics of the signal itself. However, as exemplified above, there is a growing body of case studies showing several avenues may lead to rapid advances by: (i) optical data of varying spatiotemporal resolution (as in Fig.4) can be used to bridge the scale gap between field observation and free medium-spatial high-temporal resolution imagery (e.g. MODIS or MEdium Resolution Imaging Spectrometer MERIS); (ii) using costly airborne data (especially LiDAR) as complement of field measurements prior to upscaling via optical imagery; (iii) using forest structure and radiative transfer models to help translate signal information into biophysical parameters. Indeed, at the meeting point between field and zenithal observations, structure modelling of trees and stands is likely to play an increasing role for both data integration and method validation. As a consequence, and considering the labor-intensive nature of field measurements for 3D model calibration, technological innovations are needed and awaited in the close future, especially regarding crown shape measurement. Ground-based laser scanning systems may contribute to such innovations, although the complex dense pluristrata tropical forests present a greater challenge compared to temperate forests for which promising results are reported (e.g. Watt and Donoghue 2005). Another direction for measuring 3D tree shapes is reconstructing 3D representations from multiple pictures photographed from the ground and also from climbed neighboring trees. Advances in reconstruction techniques and software (Strecha et al. 2008) open up new avenues to directly use hand-held cameras that appear as cheap and flexible devices for data acquisition on the 3D structure.

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