Published in Annals of Forest Science, 2011
DOI: 10.1007/s13595-011-0116-9

Editorial Manager(tm) for Annals of Forest Science
Manuscript Draft

Manuscript Number:

Title: Linking canopy images to forest structural parameters: potential of a modeling framework

Article Type: Research Paper

Keywords: texture analysis; remote sensing; 3D forest model; radiative transfer model; broad-leaf tropical forests.

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Abstract: Remote sensing methods, and in particular very high (metric) resolution optical imagery, are essential assets to obtain forest structure data that cannot be measured from the ground, because they are too difficult to measure, or because the areas to sample are too large or inaccessible. To understand what kind of, and how precisely and accurately, information on forest structure can be inverted from RS data, we propose a modeling framework combining a simple 3D forest model, Allostand, based on empirical or theoretically-derived DBH distributions and allometry rules , with a well-established radiative transfer model, DART. This framework allows producing forest canopy images for any type of forest based on widely available information of inventory data. Image texture can then be quantified, for instance using the Fourier Transform Textural Ordination (FOTO) method, and the derived textural indices compared with stand parameters for inversion and sensitivity analyses, as well as to indices from real world remote sensing images. The potential of the approach for the development of quantitative methods to assess forest structure, dynamics, matter and energy budgets and degradation, including in tropical contexts, is illustrated emphasizing broadleaf natural forests and discussed.

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Abstract

Remote sensing methods, and in particular very high (metric) resolution optical imagery, are essential assets to obtain forest structure data that cannot be measured from the ground, because they are too difficult to measure, or because the areas to sample are too large or inaccessible.To understand what kind of, and how precisely and accurately, information on forest structure can be inverted from RS data, we propose a modeling frameworkcombining a simple 3D forest model, Allostand, based on empiricalor theoretically-derived DBH distributionsand allometry rules , with a well-established radiative transfer model, DART. This framework allows producing forest canopy images for any type of forest based on widely available information of inventory data. Image texture can then be quantified, for instance using the Fourier Transform Textural Ordination (FOTO) method, and the derived textural indices compared with stand parameters for inversion and sensitivity analyses, as well as to indices from real world remote sensing images.The potential of the approach for the development of quantitative methods to assess forest structure, dynamics, matter and energy budgets and degradation, including in tropical contexts, is illustrated emphasizing broadleaf natural forests and discussed.

Introduction

Zenithal views of the earth surface have long contributed to forest resource inventory and planning of forest management operations(Küchler, 1967; Holdridge, 1971). Visual interpretation of aerial photographs has been used worldwide for decades to a priori delineate inventory sampling strata or to map the mosaic of forest stands on criteria relating to age, structure or dominant species(see Polidori et al., 2004 for examples of tropical applications). The classical practice shows that skilled interpreters can go beyond the mapping of strongly contrasting forest types and analyze subtler gradients of canopy aspect and map them into meaningful qualitative classes of operational value(Husch et Harrison, 1971). An important fraction of the criteria sustaining such interpretations relates to sizes and spatial distribution of both tree crowns and inter-crown gaps, which are observable on printed panchromatic outlooks of classical scale and resolution (1/30 000 or less), and are here referred to as canopy texture. Colour photos, including “false-colour” ones that display the near-infrared response of the vegetation can provide additional insights on species compositions. The practical, implicit message of this long-standing expertise on photo interpreting is that forest canopy aspect does convey valuable information about the forest stands.

However, this empirical expertise did neither translate into the definition of objective indices to quantify canopy aspect nor into the study of the relationship between canopy features and the most classical structural variables used by foresters, especially those which are routinely measured in field inventories. This is all the more regrettable that global challenges on climate and biodiversity urge forest science to design cost-effective systems to consistently monitor forest structures (i.e. the three dimensional arrangement of individual trees and tree parts)over extensive areas(Shugart et al., 2010).

While means for field measures are limited and often insufficient to regularly sample large areas of poor accessibility, especially in the tropics, the rapid improvement and diversification of satellite-borne sensors suggests that monitoring methods combining field and remotely-sensed data could provide cost-effective answers to the forest structure monitoring challenge(Asner et al., 2010). In fact, remote sensing approaches have the potential not only to extrapolate field results, but also to provide information that is near impossible to accurately measure on the ground, such as total height or crown size of canopy trees in multi-strata natural forests. Such information is critical since canopy structure conditions stand dynamics, gas and energy exchanges, forest feedbacks on the micro- and macro-climates and habitat for the canopy-specialized biota(Birnbaum, 2001; Bonan, 2008). Even though remote-sensing approaches using medium to high resolution data (pixels larger that 5 m) have been hindered for decades by the saturation of all the physical signals at intermediate levels of forest above-ground biomass (AGB, c. 200 t/ha, Imhoff, 1995; Proisy et al., 2000), the increasing availability of very high resolution (VHR) data opens new prospects. Indeed, the VHR optical images furnished by satellites (e.g. Ikonos, Quickbird or GeoEye) now approach the potential of airborne photos for visual interpretation at a cheaper cost which will keep decreasing in the future.As a consequence, several studies endeavoured to extractquantitative information on canopy structure from such imagery (Bruniquel-Pinel et Gastellu-Etchegorry, 1998; Asner et al., 2002; Frazer et al., 2005; Gougeon et Leckie, 2006; Malhi et Roman-Cuesta, 2008). In particular, texture indices provided by the FOTO method (Fourier Transform Textural Ordination) showed good correlations with usual stand parameters(Couteron et al., 2005) and even biomass(Proisy et al., 2007) in some case studies carried out in natural tropical forests. These relationships remarkably appeared to hold without saturation even for very high biomass values (above 500 t/ha).

Validating at large scale those encouraging local results is made difficult by the present lack of extensive datasets simultaneously featuring reliable field data and canopy images of sufficient spatial resolution, i.e. with pixels of 1 m or less. Moreover, the regional to global stability of the relationships between canopy structure (mostly pertaining to crowns) and other forest structural parameters (largely deriving from trunks diameters) remains to be assessed, despite some theoretical and empirical efforts to uncover general allometry rules at the individual and stand levels(Coomes et al., 2003; Muller-Landau, Condit, Chave, et al., 2006; Poorter et al., 2006; Enquist et al., 2009). Similarly, the influence on image texture of tree architecture, crown shape, physiology, phenology, and their variation across species, as well as the effect of different perturbation types on stand structure calls for in depth studies. Another issue is that acquisition conditions, and in particular the sun-scene-sensor angles which determines shadowing,do have an influence on texture which must be accounted for when using several or numerous images, or in the presence of marked topography(Barbier, Proisy, et al., 2010).

Thus, simulating canopy images from forest mockups of known 3D structure is appealing to anticipate the increasing availability of relevant satellite data, and extensively assess the extent to and the conditions under which forest structural stand parameters could be retrieved from canopy image analysis. The objectives of the approach which will be illustrated in the present paper can be summarized in four steps: (i) simulating 3D explicit mockups of forest stands from the most basic information provided by field inventories, namely distributions of diameter at breast height values (dbh) ; (ii) applying a radiative transfer model on the mockups to generate canopy images; (iii) characterizing the texture of the generated canopy images using the FOTO method; (iv) analyzing the covariation of FOTO-based texture indices and the stand parameters corresponding to the 3D mockups in order to test the potential of model inversion.

Modelling 3D stands – The Allostand model

The Allostand model aims at producing simple 3D forest simulations (Fig. 1) on the basis of information generally available out of classical forest inventories, i.e. densities of trees according to classes of trunk diameters at breast heights (DBH). The basic model input is therefore either an observed or a theoretical diameter frequency distribution, such as the inverse square law of Enquist et al.(2009) or alternative laws(Coomes et al., 2003). From there,the spatial distribution and sizes of trunks and crowns are produced on the basis of measured allometry rules at the individualand stand scales (see below).

To ensure its applicability over extents of poorly known forests, the present version of the model is kept at the simplest possible level(or "zeroth order" sensu West et al., 2009): tree crowns are modeled as ellipsoids, and no plastic deformations are implemented.From the DBH, allometry rules obtained, for instance from rainforest trees(Poorter et al., 2006; Muller-Landau, Condit, Chave, et al., 2006), allow computing tree height and crown dimensions. For instance one can compute crown area and tree height from DBH using the allometric exponents provided in table 2 of (2006). In absence of measured (x,y) positions for each tree, these positions are obtained using an iterative hard-core(Matérn, 1986) birth/death procedure. In other words, starting from the largest tree in the DBH distribution, at each iteration step a new individual of lesser or equal size is placed at random. It is kept only if it happens to be located beyond a certain distance from preexistingtrees, otherwise a new location is taken, up to a chosen maximal attempt number. If this number is reached, a failed birth is counted. Hard core distance between trees of the same size class is taken from the isometricrelationshiplinkinginter-tree distance to DBH as derived by Enquist et al.(2009) on theoretical grounds. Minimum distance between trees of different size classes are defined empirically according to a decreasing function of the diameter difference, in a way minimizing the number of failed births. The above procedure is repeated within each size class for the number of individuals requested to match the DBH frequency distribution.Model output takes the form of a table listing tree individuals, their XY positions and dimensions (height plus trunk and crown radii).

To illustrate the result of a tropical rainforest simulation produced by the Allostand model, a tridimensional representation is shown in figure 1. This simulation was created using a DBH frequency distribution following theinverse square law (-2 power law with intercept = 5000 trees/ha) and with a bin width of 1 cm, a minimum DBH of 5 cm and a maximum DBH (DBH_{max}) of 100 cm.

Modelling radiative transfer– DART model

From the 3D stands, it is possible to simulate spectral images of the scene as viewed from air- or space-borne sensors (Fig. 2). The Discrete Anisotropic Radiative Transfer (DART) model(Gastellu-Etchegorry, 2008), is used to simulate the interaction between scene components and electromagnetic signals of various natures(e.g., of varying wavelengths, active or passive signals, of varying sun-scene-sensor configurations, etc.).The DART model involves an iterative tracing of rays in a discrete number of directions within a scene constituted by parallelepipedic voxels. Light transfer within a voxel depends on the proportion and orientation of volume elements (modeled as turbid, e.g. foliage, atmosphere) and surface elements (solid, e.g. trunks, soil)it contains.

From the positions and dimensions of trees produced by the Allostand model, DARTfirst computes the voxelized (discrete) scene, which involves computing the fractions and orientation of the main scene elements present in each voxel. The reflectance of each scene element in different spectral bands can be parameterized at the desired or accessible level of precision, from either general estimations or from specific measurements made for the area of interest (for instance, for foliage, from radiometric information and technical specifications of modern satellite imagery such as GeoEye®). Other relevant parameters used by DARTare the leaves angular distribution and density within foliage voxels, as well as the distribution of empty voxels within a tree crown. As these parameters are difficult to measure, they are usually taken empirically, in order to achieve realistic values of the Leaf Area Index (LAI) at the stand scale (e.g., LAI between 6 and 8(Richards, 1995)).

Image analysis – FOTO method

The Fourier Transform Textural Ordination (FOTO) method basically ordinates digital images along coarseness-fineness texture gradients in a way congruent with the visual appraisal (see (Couteron, 2002)for details). It showed promising results(Couteron et al., 2005; Proisy et al., 2007; Barbier, Couteron, Proisy, et Malhi, 2010) for the characterization and measure of canopy texture on very high (metric) resolution air- and space-borne panchromatic imagery. The FOTO method uses a windowed 2D Fourier transform and the derived periodograms(power spectrum; Diggle, 1989; Mugglestone et Renshaw, 1998)to characterize the textural properties of image extracts of about 1 ha. Each 2D periodogram is simplified to account only for spatial frequency (scale) information and not for possible anisotropic variations of texture. This simplification (averaging of periodogram values over the azimuths) leads to a so-called r-spectrum(Mugglestone et Renshaw, 1998)representing, for each image, the broken-down of the panchromatic reflectance variance accounted for by successive bins of spatial frequencies. Principal component analysis is then applied on the set of standardized r-spectra (which may include spectra from hundreds to thousands of images)to identify the main gradients of canopy textural variation and ordinate the images accordingly. The first PCA axis generally approximates the fineness-coarseness gradient of canopy grain, most frequently linked to variations in crown sizes. Subsequent axes, when notable, may point towards specific ranges of dominant spatial frequencies (related to crown or gap sizes). PCA scores of the images against such gradients are used as continuous indices of textural variation of canopy aspect.

Example

To illustrate the interest of the Allostand+DART modeling framework, we simulated 144 panchromatic reflectance images using the same parameterization as the stands presented in figures 1 and 2, for a rangeof maximum DBH values ($DBH_{max}$from 50 to 100 cm by steps of 10 cm). To assess the sensitivity of the results to perturbations of the DBH distribution, we also madethe density in the largest DBH class vary by a factor of either0.33, 0.5, 1 or 2. For each combination of these two factors (i.e., maximum DBH and density modulation in the largest DBH class), six replicates were produced.

If we investigate the relationships (Fig. 3) between stand parametersand the main textural gradient (*PCA1*) identified over the 144 images by the FOTO method, we find that the correlation with stand density is the most sensible to the perturbation introduced in stand structure by changing the tree density in the largest DBH classes. The r^2 of the regression is indeed only of 0.35 (Fig. 3a). On the other hand, the correlation with mean crown diameter (Fig. 3b) or with the mean DBH or mean quadratic DBH are fairly good in this case, with r^2 above 0.6. The best correlations are found with the maximum DBH or the averagecrown size (Fig. 3c). This is no surprise since what is captured by texture analysis concerns the structure of the top canopy and the crown size distribution of canopy trees.

Discussion

The main purpose of this paper is to draw the attention of forest scientists and modelers on the potential of simulating canopy panchromatic images from forest mockups of known 3D structure. Simulating such images could be a decisive step to help forest monitoring and forest ecology benefit from the increasing availability of very high resolution space-borne imagery through a thorough process of model calibration and inversion. As it has been illustrated here using a very simple structure model, the simulation allows assessing the extent to which the entire modeling chain can be inverted to retrieve forest structure variables from canopy reflectance information. From such an approach it is possible to have some a priori knowledge on the magnitude of the prediction error that is to be expected for the different variables and to efficiently design how field data should be acquired to validate the inversion process in a givenecological context. In fact, the confrontation of space-borne information to field inventory data has often been hindered by field sampling units having size, shapeor spacing propertiesirrelevant to that purpose. This hindrance adding to the well-documented signal saturation problem(Imhoff, 1995; Foody, 2003)has made the results of forest variable prediction from spatial observation often disappointing andat best revealing local agreements of unwarranted extrapolation. Whatever the type of signal and the kind of signal analysis technique, progressin forest monitoring now requestssimulations of signal interactions with a wide range of known forest structures for inversion testing.This necessity has long been recognized for radar applications(Kasischke et Christensen, 1990; Proisy et al., 2000) but has been overlooked by most users of optical imagery(but see Bruniquel-Pinel et Gastellu-Etchegorry, 1998; Frazer et al., 2005; Widlowski et al., 2007).Developing and validating forest application forthe more recent full-waveform LiDAR (Light Detection and Ranging)techniques also requests signal simulation on forest mockups in a way similar to what is presented here, which can be done by adapting existing radiative transfer models (Rubio et al., 2009).

Since canopy information mostly pertains to the dominant fraction of the tree population, it is obvious that the best predictions are to be expected for stand variables that are the most strongly influenced by this dominant subpopulation (e.g. basal area, quadratic mean diameter and, of course,total above-ground biomass). As illustrated here (Fig.3), less accuracy is probable for variables related to stand density which directly integrates understory trees that are not visible in the canopy. In even-aged stands, most trees are dominant or co-dominant and logically the FOTO method yielded good predictions of total AGB for even-aged mangroves (Proisy et al., 2007).

In mixed-aged stands,canopy trees only account for a small share of the overall tree number. Yet, this fraction is expected to capture most of the limiting resource (usually light) and to condition gas and energy exchanges with the atmosphere (Bonan, 2008)and thereby strongly influence the whole stand dynamics. Enquist et al. (2009) assumed one of the simplest models of stand demography, which can be traced back to de Liocourt(1898), to reach the prediction that the diameter densitydistribution should scale as a -2 power of DBH. In the present modeling illustration, we referred to it for simplicity sake,although such a distribution is not satisfactory(Muller-Landau, Condit, Harms, et al., 2006).Other simple functions of diameter distribution predicted by competing theories(Coomes et al., 2003) may have been used as well to create families of 3D mockups. Above all, as underlined by Coomes et al. (2003) the size distribution of the largest trees is probably shaped by disturbances rather than neighborhood competition and is therefore barely predictable from a general reasoning. Since there is a top-down control on the stand structure (as in our Allostand simulation process), random variations in the abundances of larger treesalso propagate into the size distribution of smaller individuals. This is what we illustrated here by letting the density vary in the largest DBH class as a rudimentary way to parameterize a family of mockups. Ongoing developments include the simulations of mockups and canopy images from real-world diameter distributions observed by extensive inventories in central Africa.They also feature the prospect to deduce the mockups as outputs of more realistic simulators of forest dynamics (e.g. STRETCH, Vincent et Harja, 2008). However, most existing simulators are still highly context-specific and demanding in terms of costly diachronic data. They may also feature structural rules of unknown robustness outside the particular situation they have been devised to mimic.

As a consequence, simple modeling rules are still relevant to address the linking of stand structure and canopy images over extensive areas which are still devoid of reference data and simulators, especially in the tropics. The suite of modeling steps leading to canopy images should and could nevertheless be parsimoniously improved by verifying or calibrating the fundamental parameters for tree allometries and foliage reflectance for broad classes of forest. Simple simulation-based modeling approaches coupled with field case studies(Couteron et al., 2005; Proisy et al., 2007; Barbier, Couteron, Proisy, Malhi, et Gastellu-Etchegorry, 2010) have already demonstrated that some important stand parameters, including AGB, can be predicted from canopy images in heterogeneous natural forests. Enhanced modeling procedures will contribute to better assess the validity domains and the errors to be expected for such predictions.

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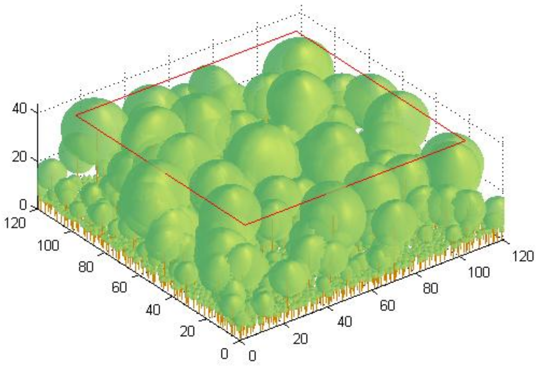

Figure 1. View of a forest stand produced by the Allostand model on the basis of a inverse square law DBH distribution(Enquist et al., 2009), and using rainforest tree allometries(Poorter et al., 2006; Muller-Landau, Condit, Chave, et al., 2006). The superimposed square area represents the 1 ha plot used in subsequent analyses.

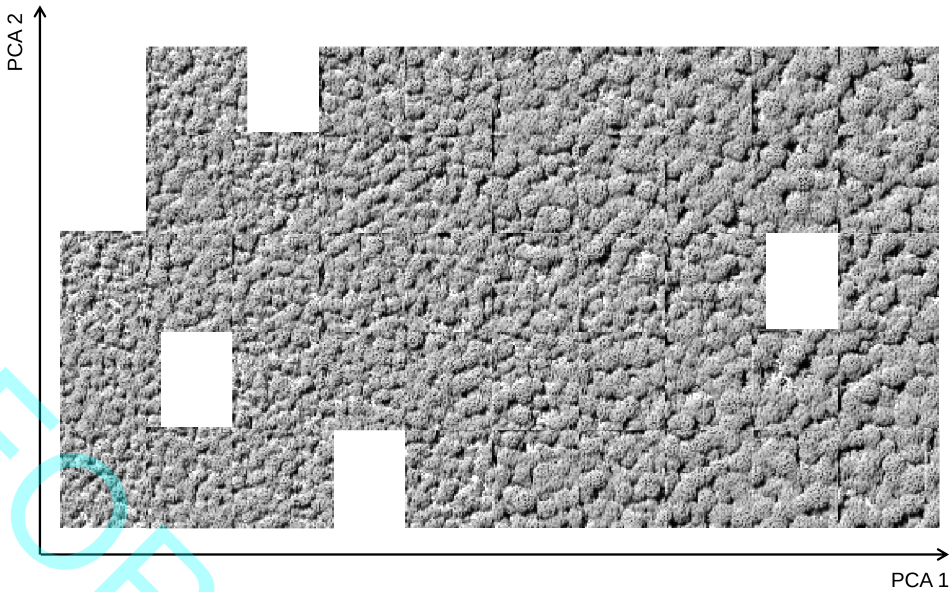

Figure 2. Array of panchromatic images produced by the DART radiative transfer model using Allostand 3D forest simulations. The images are sampled and sorted along the two main textural gradients identified by the Fourier transform textural ordination (FOTO) method applied 144 images simulated with varying DBH_{max} and density values. The main gradient (PCA 1) corresponds to aclear fineness-coarseness gradient; visual interpretation of the second gradient (PCA 2) is more difficult, but it represents density variations (see text).

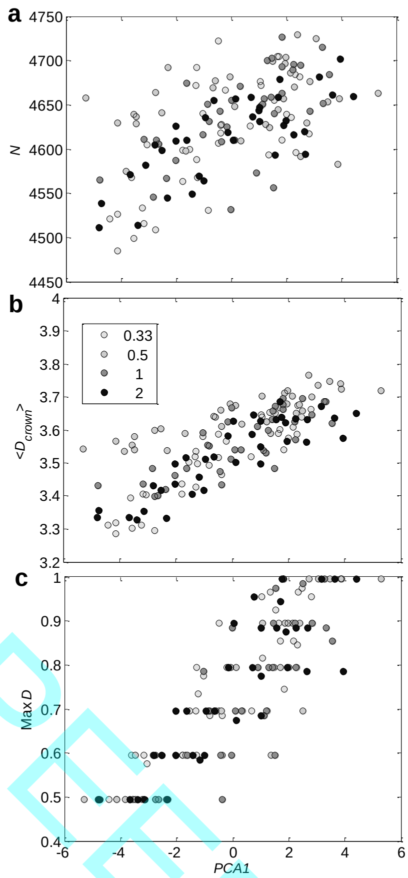

Figure 3. Relationship between some classical forest parameters of the Allostand simulated forests and the main textural gradient identified by the FOTO method on the simulated mages (*PCA1*). (a) Total stand density, [stems of DBH>2 cm ha^{-1}]; r^2=0.35. (b) Mean crown diameter [m]; r^2=0.62, (c) Maximum DBH value [m]; r^2=0.75. Allostand simulations were produced on the basis of a -2 power law DBH distribution and with varying DBH max values (50 to 100 cm by steps of 10 cm). Noise has been introduced by varying the density in the largest DBH class by a factor of either 0.33, 0.5, 1 or 2 (see inset in (b) for the symbols of the four classes).

*Title Page

Linking canopy images to forest structural parameters: potential of a modeling framework

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Running head: Linking forest canopy images to field inventory data

Keywords: **texture analysis/remote sensing/ 3D forest model /radiative transfer model / broad-leaf tropical forests**

Characters: 31 166

Figures: 3