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ORIGINAL PAPER

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

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Abstract

- ***Context*** 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.
- ***Aim*** 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 allowing to produce forest canopy images for any type of forest based on basic inventory data.
- ***Methods*** This framework combines a simple 3D forest model named "Allostand," based on empirically or theoretically derived diameter at breast height distributions and allometry rules, with a well-established radiative transfer model, discrete anisotropic radiative transfer.
- ***Results*** Resulting simulated images appear of good realism for textural analysis. 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 broad-leaved natural forests.
- ***Conclusion*** Consequently, this theoretical framework appears as a valuable component for developing inversion methods from canopy images and studying their sensitivity to structural and instrumental effects.

Keywords Texture analysis · Remote sensing · 3D forest model · Radiative transfer model · Broad-leaved tropical forests

1 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 standard practice shows that skilled interpreters can go beyond the mapping of strongly contrasting forest types and analyze more subtle gradients of canopy aspect and map them into meaningful qualitative classes of operational value (Husch and Harrison 1971). A large part 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. Color photos, including "false-color" 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.

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However, this empirical expertise was neither translated 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 structure (i.e., the three dimensional arrangement of individual trees and tree parts) over extensive areas (Shugart et al. 2010).

While means for field measures will remain 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 both micro- and macro-climates, and habitats for the canopy-specialized biota (Birnbaum 2001; Bonan 2008). For passive optical sensors (operating in the visible–near-infrared domain), approaches using medium- to high-resolution data (pixels larger than 5 m) mostly provide information on green biomass, although saturation issues are known in dense cover for leaf area index values as low as three (Huete et al. 2002). However, the increasing availability of very high-resolution (VHR) data opens new prospects. Indeed, the VHR optical images provided by satellites (e.g., Pleiades, World View, GeoEye, Ikonos, or Quickbird) 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 endeavored to extract quantitative information on canopy and stand structure from such imagery (Bruniquel-Pinel and Gastellu-Etchegorry 1998; Asner et al. 2002; Frazer et al. 2005; Gougeon and Leckie 2006; Malhi and Roman-Cuesta 2008). In particular, texture indices provided by the Fourier transform textural ordination (FOTO) method 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 (up to 500 t/ha).

Validating at large scale these 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 derived from trunk diameter measurements), but potentially also other carbon pools, 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 et al. 2006a; Poorter et al. 2006; Enquist et al. 2009). Similarly, the influence on image texture of tree architecture, crown shape, physiology, phenology, and their variations across species, as well as the effect of different perturbation types on stand structure, call 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 image texture which must be accounted for when using several or numerous images (Barbier et al. 2011), or in the presence of marked topography (Ploton 2010).

We postulate that simulating panchromatic (or multi-spectral) images from forest mock-ups of known 3D structure is appealing to anticipate the potential of very high-resolution satellite data to extensively assess forest structural stand parameters. The objective of this paper is to present a coherent framework for the modeling of canopy images of tropical rainforest, to allow linking forest structure, signal transfer, and image texture, even when only basic information is available. The steps of this framework can be summarized as follows: (a) simulating 3D explicit mock-ups of forest stands from information provided by field inventories, namely distributions of diameter at breast height (DBH) values; (b) applying a radiative transfer model on the mock-ups to generate canopy images, using available/default leaf reflectance values and leaf distribution information; and (c) characterizing the texture of the generated canopy images using the FOTO method. We will illustrate the potential of the framework to explore the covariation between texture indices and forest structure parameters.

2 Modeling 3D stands—Allostand model

Numerous forest models exist (Pacala and Deutschman 1995; Purves et al. 2008; Vincent and Harja 2008) that vary in their level of detail and the processes they consider (spatial positions of, and interactions between, individuals; plant plasticity; plant and population dynamics), as much as in their formalism (cellular automata, individual-based models, analytical equations) and in their output (stand or individual level statistics). In a tropical forest context even more than in simpler temperate stands, the problem of parameterization is daunting. The information generally available is limited to densities of trees according to classes of trunk DBH and to a few general allometry rules relating DBH to other three structural parameters. These limitations led us to develop a new model, Allostand, which aims at producing simplified 3D forest simulations (Fig. 1) on the basis of such information. Model input is therefore either an observed or a theoretical diameter frequency distribution, such as the inverse square law of Enquist et al. (2009), $N \sim \mathrm{DBH}^{-2}$, 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 individual and 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. Allometry rules obtained from rainforest trees (Muller-Landau et al. 2006a; Poorter et al. 2006) allow computing tree height and crown dimensions from the DBH. For instance, one can compute crown area and tree height from DBH using the allometric exponents provided in Table 2 of Muller-Landau et al. (2006a). In absence of measured (x,y) positions for each tree, these positions are obtained using an iterative hardcore (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 preexisting trees; otherwise, a new location is taken, up to a chosen maximal attempt number. If this number is reached, a failed birth is counted. Hardcore distance between trees of the same size class is taken from the isometric relationship linking inter-tree distance to DBH on theoretical grounds (Enquist et al. 2009). 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).

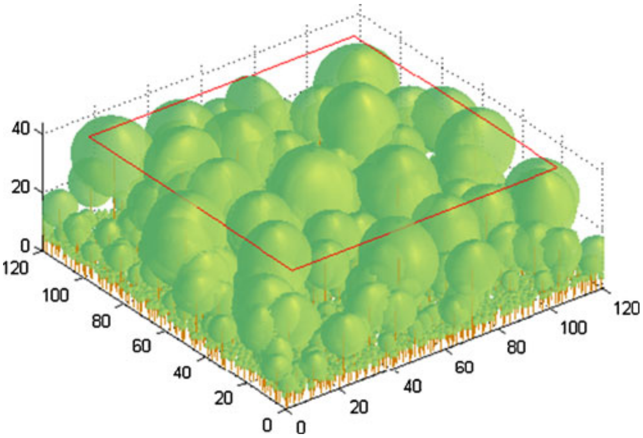

Fig. 1 View of a forest stand produced by the Allostand model on the basis of an inverse square law DBH distribution (Enquist et al. 2009) and using rainforest tree allometries (Muller-Landau et al. 2006a; Poorter et al. 2006). The superimposed square area represents the 1-ha plot used in subsequent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

To illustrate the result of a tropical rainforest simulation produced by the Allostand model, a tridimensional representation is shown in Fig. 1. This simulation was created using a DBH frequency distribution following the inverse square law (−2 power law with intercept=5,000 trees/ha) and with a DBH class width of 1 cm, a minimum DBH of 5 cm, and a maximum DBH ($\mathrm{DBH}_{\mathrm{max}}$) of 100 cm.

3 Modeling radiative transfer—DART model

From the 3D stand, 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 is the only physically realistic radiative transfer model allowing to reproduce full scene images, which is an essential asset for our purpose here. The model involves an iterative tracing of rays in a discrete number of directions within a scene constituted by parallelepiped cells (i.e., voxels). Light transfer within a cell depends on the type, density, and orientation of the scattering elements it contains. Two main types of scattering elements exist according to whether they are modeled as 2D (plane surface) or 3D (turbid medium) elements. For turbid cells, such as air and leaf cells, the scattering elements are evenly distributed within the cell. For leaf cells, the distribution also varies anisotropically following the leaf density and angular distribution parameters. By contrast, 2D elements (e.g., trunks, soil) are modeled as plane surfaces/triangles within the cell.

From the positions and dimensions of trees produced by the Allostand model, DART first computes the scene, which involves computing the fractions and orientation of the main scene elements (leaves, branches, stems, ground, etc.) present in each cell. 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. Leaf density as well as the distribution of

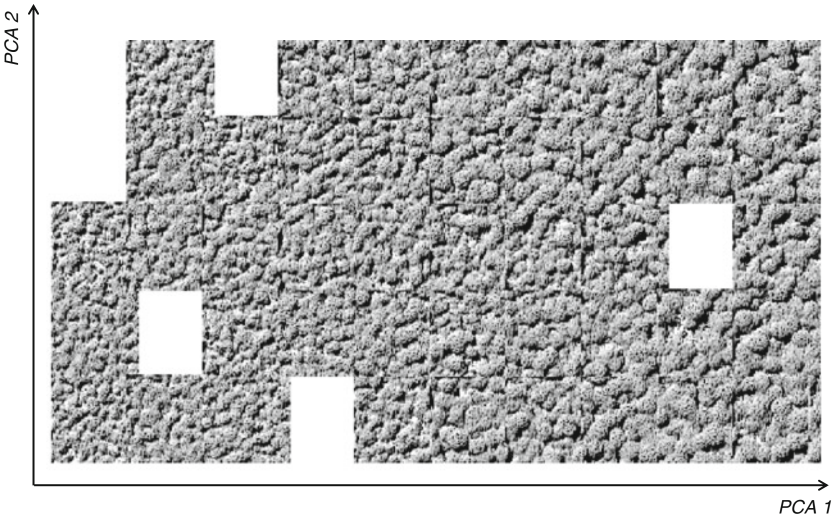

Fig. 2 Array of panchromatic images produced by the DART radiative transfer model using Allostand 3D forest simulations. The images are sampled and sorted along the two main textural gradients identified by the Fourier transform textural ordination method applied to 144 images simulated with varying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

empty cells within a tree crown may possibly be determined 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)). Importantly, there is no limitation in DART regarding the importation of more detailed information on the spatial arrangements of branches and leaves, if such information is available, which makes it a very flexible tool in combination with any type of input from forest models or field data.

4 Image analysis—FOTO method

The FOTO method ordinates digital images along coarseness–fineness texture gradients in a way congruent with visual appraisal (see Couteron et al. 2005 for details). It showed promising results (Couteron et al. 2005; Proisy et al. 2007; Barbier et al. 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 spectra; Diggle 1989; Mugglestone and 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 and Renshaw 1998) representing, for each image, the decomposition of gray level (e.g. panchromatic reflectance) variance into bins of spatial frequency. 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 dominant crown sizes. Subsequent axes, when notable, may point toward specific ranges of dominant spatial frequency (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.

5 Example of sensitivity analysis

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 Figs. 1 and 2, for a range of maximum DBH values ($\mathrm{DBH}_{\max}$ from 50 to 100 cm by steps of 10 cm). To assess the sensitivity of the results to changes in the structure of the DBH distribution, we also made the density in the largest DBH class ($N_{\max}$) vary by a factor of either 0.33, 0.5, 1, or 2. For each combination of these two factors (i.e., $\mathrm{DBH}_{\max}$ and $N_{\max}$), six replicates were produced.

If we investigate the relationships (Fig. 3) between stand parameters and 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 changes in $N_{\max}$. 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

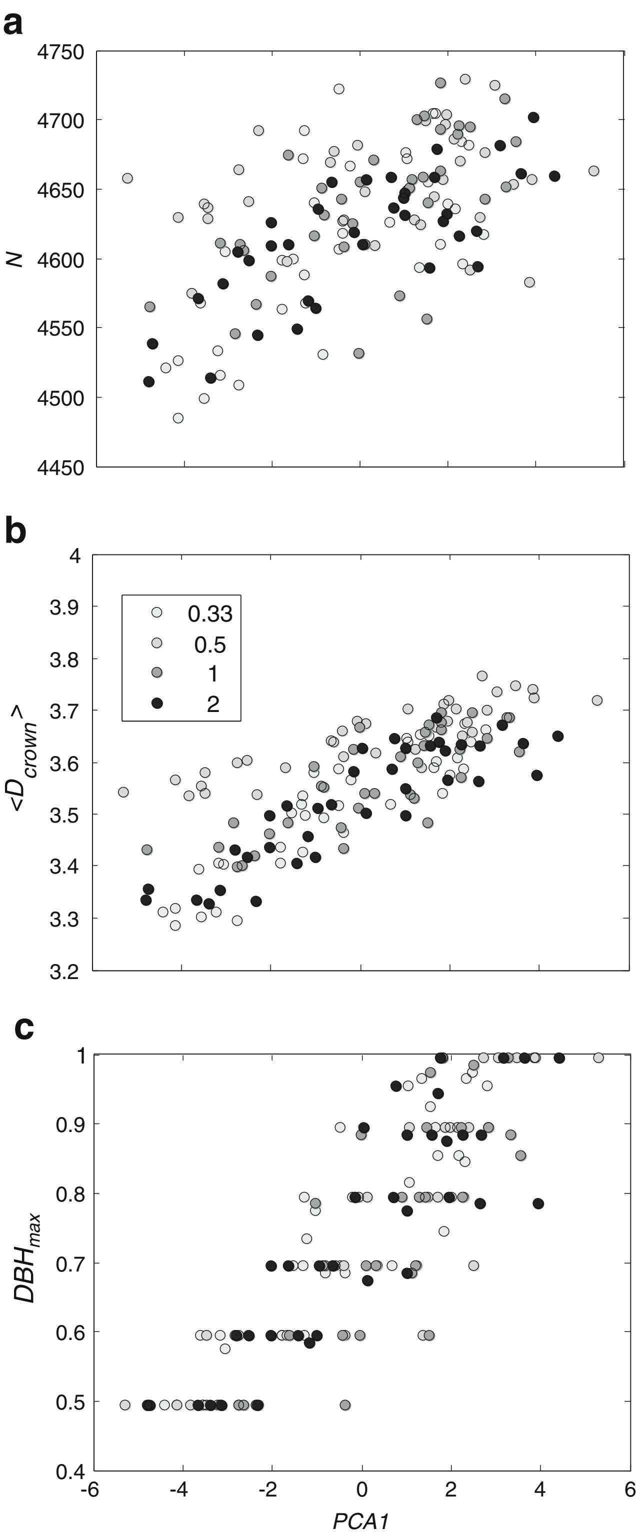

Fig. 3 Relationship between some classical forest parameters of the Allostand simulated forests and the main textural gradient identified by the FOTO method on the simulated images (PCA1). **a** Total stand density (stems of DBH>2 cm ha^{-1}); r^2=0.35. **b** Mean crown diameter (meters); r^2=0.62. **c** Maximum DBH value, DBH$_{\max}$ (meters); 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 ($N_{\max}$) by a factor of either 0.33, 0.5, 1, or 2 (see *inset* in **b** for the *symbols* of the four classes)

r^2 above 0.6. The best correlations are found with the DBH$_{\max}$ or the average crown 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.

6 Discussion

As it has been illustrated here using a very simple structure model, the simulation of canopy panchromatic images from forest mock-ups of known 3D structure is a promising way for assessing to what extent forest structure variables can be inverted from canopy reflectance information. Regarding the sensitivity to instrumental data, and in particular the variation to sun-scene-sensor geometry, the Allostand+Dart framework also allowed reproducing results (i.e., bidirectional texture functions, see Proisy et al. 2011) very similar to those obtained using a different (light detection and ranging (LiDAR)-based) framework (Barbier et al. 2011). The Allostand+Dart framework therefore allows gaining some a priori knowledge on the magnitude of the prediction error depending both on the variability in forest structure and on instrumental perturbations and to efficiently design how field data should be acquired to validate the inversion process in a given ecological context. In fact, the confrontation of space-borne information to field inventory data has often been hindered by field sampling units having size, shape, or spacing properties irrelevant 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 and at best revealing local agreements of unwarranted extrapolation. Whatever the type of signal and the kind of signal analysis technique, progress in forest monitoring now requests simulations of signal interactions with a wide range of known forest structures for inversion testing. This necessity has long been recognized for radar applications (Kasischke and Christensen 1990; Proisy et al. 2000) but has been overlooked by most users of optical imagery (but see Bruniquel-Pinel and Gastellu-Etchegorry 1998; Frazer et al. 2005; Widlowski et al. 2007). Developing and validating forest application for the more recent LiDAR techniques also requests signal simulation on forest mock-ups in a way similar to what is presented here, which can be done by adapting existing radiative transfer models (Morsdorf et al. 2009; 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 (AGB)). As illustrated here (Fig. 3), less accuracy is expected 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. When possible, a better 3D description of the forest structure can be obtained if texture information is combined with Lidar-derived forest height (Asner et al. 2010) and low-frequency radar signatures (Hyde et al. 2007).

This work actually exploits Enquist et al. (2009) assumption, i.e., one of the simplest models of stand demography, which can be traced back to de Liocourt (1898), to reach the prediction that the diameter density distribution 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 entirely satisfactory (Muller-Landau et al. 2006b). 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 mock-ups. 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 trees also propagate into the size distribution of smaller individuals. This is what we illustrated here by letting the density vary in the largest DBH class ($N_{\max}$) by nearly an order of magnitude, as a rudimentary way to parameterize a family of mock-ups. This variation did introduce a fair amount of noise, if one refers to the relationships actually found between texture and measured stand characteristics (at least in local scale studies: Couteron et al. 2005; Proisy et al. 2007; Ploton 2010). Ongoing developments include the simulations of mock-ups and canopy images from real-world diameter distributions observed by extensive inventories in Central Africa. Mock-ups could also be obtained as outputs of more realistic simulators of forest dynamics (e.g., STRETCH, Vincent and 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 relevant to address the linking of stand structure with canopy images over extensive areas which are still devoid of reference data and simulators, especially in the tropics. The succession of modeling steps leading to canopy images should nevertheless be parsimoniously improved by checking 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 et al. 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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