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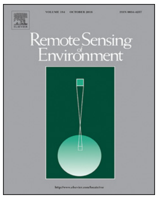

Fine-scale three-dimensional modeling of boreal forest plots to improve forest characterization with remote sensing

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ABSTRACT

Improving the quality of information that can be obtained from forest inventories can enhance planning for the best use of forest resources. In this study, we demonstrate the capability to improve the characterization of forest inventory attributes using terrestrial laser scanner (TLS) data, a fine-scale architectural model (*L-Architect*), and airborne laser scanner (ALS) data. Terrestrial laser scanning provides detailed and accurate three-dimensional data and has the potential to characterize forest plots with comprehensive structural information. We use TLS data and in situ measurements as input to *L-Architect* to create reference plots. The use of *L-Architect* for modeling was validated by comparing selected attributes of the reference plots with validation plots produced using simulated TLS data, with normalized root-mean square error (NMRSE) values below 17%. Surrogate plots were then created using a library of tree models where individual trees were selected according to three attributes—tree height, diameter at breast height, and crown projected area—either measured from in situ plots or derived from ALS data. The accuracy of the surrogate plots was assessed by comparing several key forest attributes from the reference plots, including branching structure (e.g., number of whorls, knot surface), crown shape and size (e.g., base height, asymmetry), heterogeneity (e.g., lacunarity, fractal dimension), tree volume, and the spatial distribution of material (e.g., Weibull fit, leaf area index). Overall, the surrogate plots reproduced the attributes of the reference plots with NRMSE mean value of 17% ($R^2 = 0.68$) using in situ ground measurements and 24% ($R^2 = 0.51$) using inputs estimated with ALS. Some attributes, such as leaf area index, knot surface, and fractal dimension, were well predicted ($R^2 > 0.80$), whereas others, like crown asymmetry and lacunarity, had weak correspondence ($R^2 < 0.16$). The ability to create surrogate forest plots with *L-Architect* makes it possible to estimate detailed structural attributes that are difficult to measure with conventional forest mensuration techniques and that can be used for model calibration with above-canopy remote-sensing data sets.

1. Introduction

Accurate and up-to-date information regarding the state, health, and development of forests is needed to quantify and predict, among other things: (i) the canopy–atmosphere exchange of material and carbon (C) fixation, (ii) the spatial dynamics of cover from forested to nonforested resulting from disturbance or fire, (iii) the radiation regime within the canopy, (iv) the biophysical and biochemical properties of forests, (v) the dynamics of biodiversity and habitats, and (vi) the available resources for the timber industry to support sustainable

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Abbreviations: ASYM, crown asymmetry; BR, branchiness ratio of the largest branch diameter to the diameter at breast height; B_{tot}, total number of branches; CBH, crown base height; CHM, canopy height model; CPA, maximum crown projected area; CRMSE, centered root mean square error; CSA, canopy surface area; CSV, canopy surface volume; CW, maximum crown width; DBH, diameter at breast height; D_δ, fractal dimension; FC, fraction cover; HCPA, height at maximum crown projected area; HGT, total height; HLC, height to live crown; K_{surf}, total knot surface on the main stem; LA, total leaf area; LAI, leaf area index; NRMSE, normalized root mean square error; PAI, plant area index; R, correlation coefficient; R^2, coefficient of determination; RMSE, root mean square error; T_{coef}, stem taper coefficient; VOL, crown volume; W_{tot}, total number of whorls; W_α^{leaf}, scale parameter of the leaf area Weibull distribution; W_α^{wood}, scale parameter of the wood volume Weibull distribution; W_β^{leaf}, shape parameter of the leaf area Weibull distribution; W_β^{wood}, shape parameter of the wood volume Weibull distribution; Λ, lacunarity index of tree and plot canopy structure; Λ_{CHM}, lacunarity index of the canopy height model; σ_{CHM}, standard deviation of the canopy height model

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management. Remote sensing has proven to be a useful tool to monitor forest environments by providing repetitive measurements within a wide range of spatial, spectral, radiometric, and temporal resolutions. Interpretation of remote-sensing data requires the use of numerical methods and quantitative models. These models explain the nature of the measured physical signal (Chen and Leblanc, 1997; Disney et al., 2000; Gastellu-Etchegorry et al., 1996; Govaerts and Verstraete, 1998; Widlowski et al., 2006), characterize the state of the system under observation (Ceccato et al., 2002; Myneni et al., 2002; Pinty et al., 2006; Verstraete et al., 1996) or quantify empirical relationships between the variables of interest and the remote measurements (Koch, 2010; Luther et al., 2014; van Leeuwen and Nieuwenhuis, 2010; Wulder et al., 2004, 2012). The complexity of the three-dimensional (3D) forest structure has largely contributed to the use of empirical models because of the difficulty in defining an exact estimate of the state variables—such as structural attributes—of the observed system. Progress towards the development of models linking remote-sensing data with structural attributes or other derived variables largely depends on the ability to characterize the structure of forest stands with proper ground data.

Although some forest structural attributes can be measured directly in the field (e.g., stem diameters and tree heights), practical constraints prohibit the measurement of fine-scale structure. The number of trees or plots that can be measured is often limited by transportation issues for remote locations, practical aspects of working in harsh environments, and required financial/logistical resources. Conventional forest inventories focus on measuring several key structural attributes at the tree and plot levels, mostly related to wood volume (Avery and Burkhart, 2002; Kangas, 2010). Measured plot-level attributes usually consist of species composition, an approximation of height and forest cover, characterization of the soil, drainage, site potential, and in some cases, a description of the understory. Measured tree-level attributes usually consist of the species, stem diameter at breast height (DBH), height, and qualitative estimates of crown quality, vitality, and health. These attributes are useful for volume estimation but they are limited in their ability to characterize fine-level structures. Generally, the measurement of fine-scale structural elements of forest canopies requires destructive sampling with intensive field work (Champion et al., 2001; Landry et al., 1997). Measuring fine-scale structural attributes requires such intensive measurement that it is rarely undertaken, and if so, it only includes a few plots because of resource limitations (Calders et al., 2015; Gonzalez de Tanago et al., 2017; Stovall et al., 2017). Therefore, alternative methods are required to estimate fine-scale tree- and plot-level structural attributes.

Light detection and ranging (LiDAR) systems provide 3D returns from canopy elements. In particular, airborne laser scanners (ALS) are well suited to characterize the shape of the canopy surface. Stand biomass, height, and the vertical distribution of forest structure are now routinely estimated using ALS data (Bouvier et al., 2015; Kankare et al., 2013; van Leeuwen and Nieuwenhuis, 2010; Wulder et al., 2012). These estimates of structural attributes characterize forest ecosystem structure, diversity, and function at finer spatial and temporal scales than previously possible. Terrestrial laser scanners (TLS) collect large amounts of 3D data on the fine-scale structure of trees and forest stands (Dassot et al., 2011). The detailed 3D tree and canopy structure information obtained from TLS is invaluable for the validation of above-canopy remote sensing measurement and derived products (Calders et al., 2018; Widlowski et al., 2015). For each TLS scan, millions of returned signals are registered, providing positional information on all elements surrounding the instrument. Despite the potential for TLS to generate high quality data, these data can be unreliable when acquired in natural forest environments. The main problem for a complete measurement of a specific scene is the occlusion (often referred to as shadowing) of the laser pulse. Groups of clustered or opaque objects prevent detection of elements in occluded areas (Hopkinson et al., 2004; van der Zande et al., 2006, 2008; Watt and Donoghue, 2005). Moreover, it is not easy to distinguish between wood and foliage material from the return signal with current instruments (Béland et al., 2014). Thus, even when scans from different points of view are available, identification of structural elements and construction of a topologically and geometrically correct 3D structure relies on architectural quantitative modeling (Côté et al., 2011; Hackenberg et al., 2014; Raumonen et al., 2013).

As an exact representation of the forest structure is not possible in practice, 3D architectural models provide convenient simplifications of forest structure at tree, branch (Cescatti, 1997; Livny et al., 2011), and down to the individual conifer shoot or leaf level (Pirk et al., 2012; Potapov et al., 2016; Widlowski et al., 2014; Xu et al., 2007). Representing tree structure is particularly challenging when dealing with mature trees in complex environments (Palubicki et al., 2009; Runions et al., 2007). In such cases, 3D architectural models have to deal with a high level of competition (between and/or intra species) for space, light and nutrient resources, which increases the number of unknown variables required to reproduce realistic forest scenarios. Several mathematical formalisms are available to express tree architecture (Godin, 2000; Godin and Caraglio, 1998; Prusinkiewicz and Lindenmayer, 1990). Among them, is the *Open L-Systems* formalism proposed by Měch and Prusinkiewicz (1996) to control branch growth and foliage addition within the tree crown. Based on *Open L-Systems*, the *L-Architect* (LiDAR to tree Architecture) model was developed to address limitations inherent in the TLS point cloud to extract the stem and main branches and then to construct the fine branching structure with the addition of foliage (Côté et al., 2009, 2011, 2012). *L-Architect* was further improved and validated using structural measurements for two coniferous species found in Newfoundland (Canada), namely, *Abies balsamea* (L.) Mill. (balsam fir or hereafter referred to as fir) and *Picea mariana* (Mill.) B.S.P. (black spruce or hereafter referred to as spruce) (Côté et al., 2013). *L-Architect* is thus capable of simulating fir and spruce trees, but procedures to simulate "surrogate" plots remain to be developed.

Surrogate plot simulation with *L-Architect* provides fine-scale structural attributes of all the trees of the plot. This method has the potential to improve on the development of empirical relationships (Mahoney et al., 2018), the calibration of growth models (Falkowski et al., 2010) and the retrieval of biophysical properties (Gastellu-Etchegorry et al., 2015) with remote sensing observations in support of large-area mapping of forest attributes. Consequently, the general objective of this study was to develop and validate procedures for creating surrogate plots with *L-Architect*. Specific objectives were to (i) create a series of "reference plots" using trees scanned with TLS, (ii) validate *L-Architect's* ability to simulate plot-level attributes using an independent set of "validation plots", (iii) create "surrogate ground plots" with a library of trees that are not necessarily collected at the plot and (iv) expand the application of *L-Architect* to generate "surrogate ALS plots" from above-canopy remote-sensing data. For clarity, the reference plots – created using trees scanned with TLS – provide the base for evaluating the capability to generate detailed tree- and plot-level attributes with *L-Architect*. The validation plots – generated with simulated TLS data – serve to validate that *L-Architect* produces results close to reality. The surrogate plots – generated with just a few key attributes measured in situ or simulated with ALS data – generalize spatially the simulations from either the ground plots or the ALS data and provide the fine-scale calibration data.

2. Material

2.1. In situ measurements

The study made use of a network of permanent sample plots (PSPs) located in Newfoundland, Canada (Fig. 1) and representing the eastern extent of the boreal forest region of North America (Rowe, 1972). Permanent sample plots are routinely measured by the provincial forest management service of Newfoundland and Labrador (Newfoundland