JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 102, NO. D24, PAGES 29,445–29,454, DECEMBER 26, 1997

Hierarchical characterization of canopy architecture for boreal forest

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Abstract. Canopy architecture, the geometric organization of aboveground vegetation, provides an essential link between patterns observable by remote sensing and fundamental ecological processes. As part of the international Boreal Ecosystem-Atmosphere Study (BOREAS); (1) we developed a hierarchical approach for sampling canopy architecture, and (2) we acquired a comprehensive data set for characterizing canopy architecture for the major BOREAS study sites. The approach involves a series of four sets of measurements at different spatial scales, ranging from the ecosystem to the leaf level: (1) regional characterization, involving measurements of the climate, ecosystem, and landscape features; (2) stand characterization, involving measurements of crown geometry (diameter at breast height (DBH), height, and crown extent), individual tree location, and understory cover; (3) tree vectorization, involving detailed sampling of the three-dimensional distribution of canopy elements and crown form; and (4) characterization of canopy geometry as seen from beneath, involving acquisition of a multitemporal catalog of hemispherical photographs. The last three sets of measurements were then used to reconstruct the three-dimensional geometry of the canopy. By comparing simulated hemispherical views upward from beneath this reconstructed canopy with in situ hemispherical photographs, the methodological approach was validated. Simulated photographs faithfully reproduced patterns observed for in situ hemispherical photographs, in particular, for gap fraction distributions of the middle ranges of zenith angles (20°–70°). Moreover, simulation of the gap fraction for this middle portion of the zenith angle was insensitive to exact mapping of the stand. The hierarchical data acquisition approach, involving mapping of tree locations and tree reconstruction, permits realistic representation of canopy material distribution. Our approach and our comprehensive data set provide a solid basis from which to integrate data gathered at the stand and tree scales, and a powerful tool for the simulation of the light regime anywhere in the canopy.

1. Introduction

The understanding of biophysical processes at work in a complex ecological system, such as a forest canopy, requires detailed knowledge of its components. The detailed three-dimensional (3-D) organization of these components will henceforth be referred to as canopy architecture. Modeling forest canopy biophysiological processes not only requires sound working hypotheses, but also realistic characterization of canopy architecture at an appropriate scale for the targeted problem. Questions of scale are at the heart of major research problems in biology and remote sensing, including the modeling and measuring of radiative transfer, carbon balance, and evapotranspiration [*Ehleringer and Field*, 1992]. Canopy architecture plays a central role in models of atmosphere-ecosystem fluxes. Moreover, it couples micrometeorology with the disciplines of remote sensing and terrestrial ecology. In essence, canopy architecture modifies biophysical climatic inputs, such as incoming solar radiation, to form microclimate. With respect to remote sensing, a canopy is a complex surface that modifies incoming solar radiation to produce measurable patterns of reflected radiation [*Goel*, 1988; *Hall et al.*, 1991; *Schaaf and Strahler*, 1993]. With respect to ecology, canopy architecture determines microclimate and thereby regulates ecophysiological processes that determine exchanges of heat, water, and carbon [*Baldocchi et al.*, 1988; *McNaughton*, 1989; *Mooney et al.*, 1987]. At population and community levels, these physiological responses are, in turn, expressed in terms of the growth, survival, and reproduction of canopy plants. The effects of microclimate on ecological processes feed back to the

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Paper number 96JD03879.
0148-0227/97/96JD-03879$09.00

Table 1. Ground Truth Measurements and Their Relative Scale in the Forest Canopy

Spatial Scale of Interpretation	Parameter Measured	Methodology
Regional	Climate, ecosystem, landscape parameters	Climate statistics; maps (topography, soil, etc.); interpretation of aerial photographs
Stand	Hemispherical views of canopy architecture	Catalog of hemispherical photographs
Stand	Tree location; understory mapping	Site characterization
Individual crown	Height of tree, live crown; trunk diameter at breast height; crown horizontal extent	Site characterization
Trunk and branch units	Trunk inventory; branch segments geometry and position; branch segments topology	Vectorization
Foliage	Geometric description of foliage	Vectorization

canopy architecture, which in turn, affects successional trends toward a climax stage.

The complexity of canopy architecture makes it difficult to quantify and translate its impact on ecological processes and patterns measurable by remote sensing. Measurement at a scale coarser than the scale of the dominant canopy element can jeopardize the successful interpretation of remotely sensed measurements. Three major problems arise in measuring detailed architecture of forest trees: (1) the high degree of variability at all scales of organization, (2) the large number of measurements required to satisfactorily describe the geometry, and (3) the practical constraints of measuring tall trees in a harsh environment.

The primary goals of this paper are to explain a conceptual and methodological approach for characterizing canopy architecture, and to validate this methodology by (1) simulating the 3-D architecture of a forest stand, and (2) comparing simulated with in situ (i.e., in the field) hemispherical photographs taken within a mapped plot. This approach was employed to provide links between disciplines involved in large ecosystem field experiments. The work was also done in support to the Boreal Ecosystem-Atmosphere Study (BOREAS) field experiment, which seeks to "improve our understanding of the interactions between the boreal forest biome and the atmosphere in order to clarify their roles in global change" [*Sellers et al.*, 1991; *Hall et al.*, 1993]. BOREAS assembled a large multidisciplinary team of scientists, in the fields of remote sensing, meteorology, ecology, and hydrology, to conduct research in Canadian boreal forests. This involved pilot studies from 1992 to 1993, intensive field work in 1994 and 1996, and data analysis and monitoring from 1995 to 1997. The BOREAS project represents, by all standards, an ambitious field and modeling effort involving a wealth of ground truth and remote sensing measurements. Our research team was responsible for designing a ground-based means for characterizing canopy architecture. By employing a hierarchical sampling approach for all major BOREAS study sites, ranging from the detailed site characterization to the fine-scale characterization of individual trees, we provide essential links between remote sensing and ecology.

2. Characterizing Canopy Architecture

2.1. A Hierarchical Characterization Approach

In preparation for the BOREAS project, the hierarchical data collection approach was tested in the context of another multidisciplinary study at the Petawawa National Forestry Institute [*Gauthier et al.*, 1992]. A complete hierarchical characterization data set comprises information gathered at all scales encompassed by the canopy elements (Table 1). This approach was inspired by the process involved in aerial photointerpretation. Most photointerpretation manuals [*Avery and Berlin*, 1992; *Spurr*, 1960] emphasize that, to maximize the probability of a good decision, the assessment of vegetative cover should be a multistage process that involves gathering and synthesizing information at different levels. Photointerpreters typically gather information from the more general, at coarser scales, to the more detailed, at finer scales [*Sayn-Wittgenstein*, 1960; *Fournier et al.*, 1995]. While photointerpretation may be successful from simple visual descriptions at several scales, a hierarchical site characterization must provide quantification of canopy architecture at all scales. Furthermore, describing canopy architecture assumes a detailed description of canopy components. Hence a successful characterization depends on realistic physical description and spatial distribution of the dominant components at each significant scale.

The hierarchical characterization approach includes three broad levels of information: regional, stand, and tree crown. The regional level involves a quantitative description of climatic, ecosystem, and landscape variables for the forest sites. The next two levels focus on canopy elements at increasingly detailed scales: the stand and the individual tree crown levels. A multitemporal catalog of hemispherical photographs constitutes a convenient record of the visual features of each canopy at these two levels. The stand level field data acquisition involves mapping tree position, measuring trunk diameter at breast height (DBH), estimating crown height, dominance, and shape, and mapping understory cover. The finest level of data acquisition provides a database on the 3-D distribution of the leaf and branch segments. More specifically, it describes the organization of branch units and foliage within representative crowns of selected species.

The hierarchical characterization data set is designed to support a wide range of scientific studies. Twelve BOREAS sites were selected to include stands of typical species of the boreal forest, namely, black spruce, jack pine, aspen, and a mixed successional site of aspen and white spruce. The hierarchical characterization method is best understood by means of a concrete example. Therefore the following analysis focuses on information collected in one BOREAS study site: the old jack pine (OJP) site in the southern study area (SSA), near Candle Lake, Saskatchewan.

Table 2. List of Some Descriptors for the Old Jack Pine–Southern Study Area BOREAS Experiment Site at the Regional Scale

	Descriptor
Geographic location	Latitude, 53.915992; longitude, −104.692466
Geographic landmarks	White Gull Creek
Surficial geology	Glaciofluvial outwash plain/Eolian hummocky dunes/organic bog
Elevation	523 m above sea level
Topography	2–5% slope, gently sloping to gently and roughly undulating
Growing season	Mid-May to late September
Average annual temperatures	0.1°C
Average precipitation	398 mm (annual); July minimum/maximum, 24.2/10.6 mm
Soil composition	Dominant soil type is Degraded Eutric Brunisol; well-drained, sandy; organic layer is 10–15 cm deep. Parent material is coarse textured, weakly to noncalcareous, sandy glaciofluvial, and sandy glaciolacustrine deposits, some of which have been reworked by wind.
Stand composition (from aerial photography and site survey)	Jack Pine (*Pinus banksiana*) dominates; average 1320–1380 live stems/ha; 11–15 m height
Stand history	Age of origin, 1910
Secondary tree species	Very scattered white birches
Dominant understory	Understory shrub layer of green adler (*Alnus crispa*); understory ground cover of feather moss (*Pleurozium schreberi*), bearberry (*Arctostaphylos uva-ursi*), and lichens (*Cladina spp*)
Other	Standing tree trunks covered by lichens (*Cladina sppo*)

Canopy Closure	Bearing, deg azimuth	% Closure (Average ± s.d.)	Transect Length, m
	270	54 ± 10	500
	120	60 ± 6	300
	20	72 ± 5	300

Descriptors are from *Evans* [1993] and *Sellers et al.* [1994, pp. 2–30].

2.2. Regional Characterization

First, general site descriptors, at the regional scale, were acquired. This regional characterization facilitated the planning of data collection for successively finer scales. For instance, a general description of the targeted forest was mandatory to the selection of a typical stand plot. The key information at that level included descriptors of the climate, ecosystem, and landscape features, such as geographic location, proximity of geographic landmarks, insolation, precipitation, length of growing season, general soil composition, general hydrology, and stand history. These descriptors are usually easily obtainable from topographic maps, forest stand maps, soil maps, interpreted aerial photographs, and climatological reports. An example of these descriptors is given in Table 2 for the OJP-SSA site as provided in the BOREAS investigator handbook [*Evans*, 1993] and the BOREAS experimental plan [*Sellers et al.*, 1994]. Regional- and ecosystem-scale descriptors then provide the context in which to better understand the general ecophysiological conditions and interdependencies of a targeted stand. Such regional characterization therefore delimits the expected range of the descriptive canopy variables. However, the general nature of regional and ecosystem scale is not sufficient for the characterization of stands. A finer description is required.

2.3. Stand Characterization: Mapping and Allometry Methodology

The next aspect of our methodological approach consisted of site characterization, which produces a stand map of individual crown locations and dimensions. Mapped plots, with typical dimensions of 50 m by 60 m, were placed in representative stands, similar in composition, age, and soil drainage as determined by aerial photograph interpretation. The stands were generally selected to be relatively uniform over a sufficient area that they could be readily observed from satellite imagery. A grid, consisting of painted stakes placed every 10 m, was installed to establish the coordinate system for all measurements. The mapped plots serve two functions: (1) to provide comprehensive canopy architecture measurements for a site representative of a specific type of forest; and (2) to provide a study area for field measurements, such as studies of light regime and tree population dynamics. Each tree in the mapped plot was labeled with numbered aluminum tags nailed to the trunk at eye level. All measured parameters refer to the tree identification numbers.

Once the reference grid was set up and the trees were labeled, we recorded a comprehensive set of site characteristics (see Table 3), in particular, measurements of location, DBH, height, and crown extent for trees within the plot. In addition, we produced a map of understory cover. First, we mapped X, Y positions of all trees relative to the grid coordinate system. This mapping was done following a fast triangulation method [*Quigley and Slater*, 1994]. Next, we measured the DBH of all trees and categorized every tree crown into standard forestry dominance categories [*Kraft*, 1884]: dominant, codominant, suppressed, dead standing, or dead leaning. Then stand-specific allometric relationships were established to permit calculation of height from DBH [*Assmann*, 1970] based on a statistically significant sample of tree height measurements (Figure 1). In addition, typical crown horizontal extent (radius) was estimated visually for a subsample of tree crowns ($n \cong 50$) throughout the plot and in four azimuthal directions. Where warranted, terrain topography was estimated. Finally, understory cover was characterized by dividing the mapped plot into 10 m by 10 m subplots, hand drawing maps of coverage of the main understory features for each subplot, and identifying major plant and lichen species within each cover class. A catalog of color photographs was acquired. These photographs

Table 3. Measurements, in the Mapped Plot, for the Stand Level Characterization

Measurement Descriptor	Applied on
Tree position	All trees
Trunk's DBH	All trees
Dominance category	All trees
Tree height	A significant sample (at least 5% of population)
Crown horizontal extent	A significant sample for at least four azimuthal directions
Understory map	All quadrants (10 × 10 m) of mapped plot
Percent coverage of understory species	All quadrants (10 × 10 m) of mapped plot
Context color photographs	Several quadrants of mapped plot

provide views of understory for each of the 10 m by 10 m subplots as well as overall views of the canopy.

2.4. Tree Vectorization: Within Crown Architecture

Our canopy characterization approach involves detailed measurement of individual tree crown architecture. To measure material distribution at the leaf/branch-segment level, we adopted a technique known as the tree vectorization method (R. Landry et al., Tree vectorization: A methodology for characterizing tree architecture in support of remote sensing models, submitted to *Canadian Journal of Remote Sensing*, 1997). This method, hereafter called vectorization, was developed to address the need for fine architectural information in support of modeling studies in remote sensing. In essence, the goal of the method is to reconstruct a statistically accurate 3-D representation of canopy components, by means of judicious subsampling. The vectorization method involves the acquisition of four types of data: (1) inventories of trunk and branch parameters, (2) the subsampling of key 3-D branching structures, (3) the foliage distribution in the crown, and (4) the dimension and arrangement of leaves. It was decided, in light of field work constraints, that the team of four field workers would collect the tree vectorization data from one forest tree per day. Tree selection relied primarily on the field crew's experience with similar forest environments combined with known statistics on the stand. The selected trees were cut to access the live crown. Once felled, the tree trunk was cut in segments of approximately 1 m throughout the length of the live crown. Each of these segments was placed on a stand in their original vertical position for further measurements. These measurements included, first, the height on the trunk, the elevation, the azimuth, and the base diameter of all the primary branches. Second, the detailed 3-D structure was measured for at least seven primary branches, usually one per section and two in the top section. In order to fully represent the key architectural elements of the 3-D branching structure, a sampling of the branch segments was executed. More specifically, a path through the available segments of the selected primary branches was decided following a sampling rule: one side branch is selected for sampling at every third of the total length of the selected main branch and side branches. For all the segments selected through this procedure, the spatial information and all segment attributes were collected using a theodolite. These attributes included a unique segment identification number, the position of the segment's end node in the cylindrical coordinate system of the tree, and the segment's child(s) and parent identification numbers. Third, the amount of foliage was estimated for all of the sampled branch segments. More specifically, the percent of foliage coverage of each sampled segment was stored as an attribute while collecting segment coordinates with the theodolite. Fourth, the dimensions and spatial organization of the leaves were measured. This involved measuring

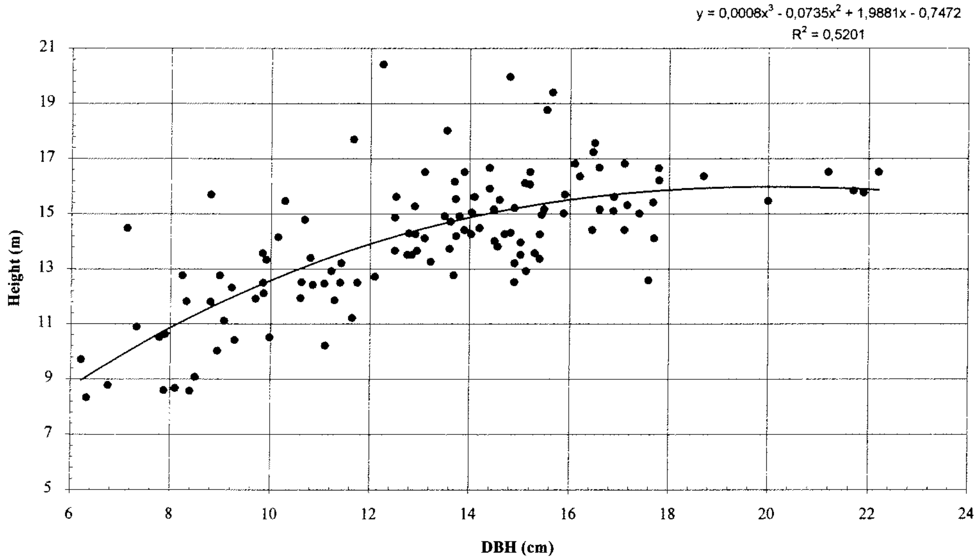

Figure 1. Allometric relationship used to predict height from diameter at breast height (DBH) for the OJP-SSA site.

length, width, and number of needles per unit branch length, as a function of crown position and leaf age class.

Finally, the information from all levels was combined and used to reconstruct trees digitally. This reconstruction procedure occurred at two levels: for the nonsampled segments of the selected primary branches and for all the primary branches not selected for detailed measurements. First, this implied that all nonsampled segments of the selected primary branches were simulated following self-similarity principles. Since the segment attributes of nonsampled segments were known, a cloned segment was taken from the branch section sampled with the most similar characteristics. Second, the primary branches other than those selected were reconstructed based on the measured basal diameter, elevation, and azimuth. These branches were simulated as a scaled replicate of the selected primary branches in the same trunk section. Scaling is done by subtraction or addition of branch segments. Thus the tree reconstruction resulted in a modeled 3-D distribution of the basic components of a tree from judicious sampling. Three representative jack pine trees were vectorized at the OJP-SSA BOREAS site: a dominant, a codominant, and a suppressed tree.

2.5. Hemispherical Photography: A Catalog of Stand Geometry as Viewed From Beneath

An important aspect of our canopy characterization approach includes the acquisition of a multitemporal catalog of hemispherical photographs, taken throughout the growing season from May to September. Hemispherical photography involves taking photographs beneath a forest canopy looking upward through a 180° wide-angle (fish-eye) lens. Arrays of hemispherical photographs were taken at standard heights (0.7, 1.5, and 2.5 m) at permanent sampling locations within mapped plots. A series of hemispherical photographs was acquired in situ for most BOREAS study sites. These photographs were then analyzed to describe the geometry of sky obstruction by canopy elements and the distribution of canopy openings, often called gap fraction [*Rich*, 1989, 1990; *Chen et al.*, this issue]. Hemispherical photographs can be used (1) to estimate solar radiation flux transmitted through the canopy openings [*Pearcy*, 1989] and (2) to calculate leaf area index (LAI) for the site [*Chen*, 1996; *Welles*, 1990; *Norman and Campbell*, 1989; *Rich et al.*, 1993]. Ongoing research on indirect methods for LAI measurement has led to significant improvements in ability to extract LAI values from hemispherical photographs. Consequently, the permanent visual catalog of stand architecture, constituted by multitemporal hemispherical photographs, provides a convenient medium for both visual and quantitative assessment of the canopy architecture at the stand and tree crown levels. In this study, a series of simulated hemispherical photographs were generated from a synthesis of in situ measurements at the stand and crown levels. The validation of the hierarchical characterization methodology hinges on the comparison between 10 simulated and in situ hemispherical photographs for the SSA-OJP BOREAS site.

3. Validation of the Methodological Approach

3.1. Outputs From the Tree Vectorization

The final reconstruction of a complete tree by the vectorization method has two usable outputs: a summary of the main architectural components, and a detailed description of each segment's position with its associated attributes (diameter, proportion of foliage in each age class, segment topology). The first output results are useful, in that they are a summary of architectural components which describe crown material distribution, which in turn, can be generalized to the whole canopy. For example, total biomass and LAI can be estimated by integrating these general values for the stand. Moreover, general crown and canopy estimates can provide realistic input for geometrically explicit forest canopy models. The results from the summary output are used primarily to highlight and understand general architectural trends for each species. Integrating these general values, at the crown level, permits realistic comparisons between sites and species. The summary of tree reconstruction highlights differences between the amount and the distribution of material for each selected species, such as total number of leaves, total foliage surface, branching surface, and basic tree element dimensions.

The second type of output from the tree vectorization consists of detailed architectural representation for all tree segments. This output was designed for the modeling of light obstruction at a fine spatial resolution. Hemispherical photographs can be modeled based on the 3-D representation of tree material densities (trunk, branches, and foliage). The reconstruction procedure produced a 3-D representation of the selected tree. An example of this tree reconstruction is shown in Figure 2 as a 3-D wire representation of tree segments for a jack pine at the OJP-SSA BOREAS site. The 3-D representation of tree material was then translated from a mesh diagram into a cubic volume or 3-D lattice. The tree was thus modeled, in the cubic volume, as a series of 3-D cells (or cubes) of identical dimension and containing material density information. The cell's dimensions were scaled as a compromise between the dimension of foliage clustering and the computing requirements. For instance, our sensitivity analysis showed that cells with 10 cm per side were representative of the jack pine foliage distribution. Larger cell size generated light obstruction patterns unrealistically larger than those observed in the in situ hemispherical photographs. The 3-D visualization of the detailed tree architecture shows the importance of the branching structure, foliage clumping, and openings. The data set collected at BOREAS showed that jack pine foliage consists of needle clumps strongly aggregated in compact tufts. The randomness of branch orientation and the openness of the tree branching distribution were also distinctive. In conclusion, the tree vectorization method enabled detailed reconstruction of canopy architecture at the scale of individual trees.

3.2. Model to Simulate Hemispherical Photographs

A critical means for validating the canopy reconstruction model involves comparing complex patterns of geometry in the simulated canopy with patterns that are measurable in the real canopy. Such a validation is accomplished by comparing results from simulated and acquired in situ hemispherical photographs. This comparison also enables us to test whether the simulated canopy has the same pattern of gaps and material clustering as does the real canopy. Thus a ray tracing model was developed to simulate hemispherical photographs based on the site characterization and the vectorization data sets [*Fournier et al.*, 1996]. Four types of input were required for this model: (1) knowledge of the optical properties of the camera and fish-eye lens, (2) viewing geometry, (3) a map of the location and DBH for each tree within the field of view, and (4) a 3-D representation of the tree material distribution for each tree (foliage, branches, and trunk). All modeled rays

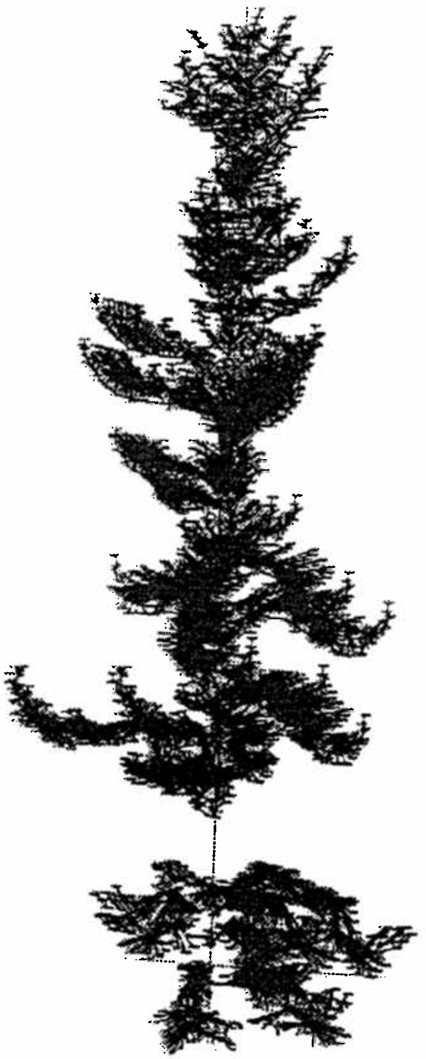

Figure 2. A 3-D wire representation of all jack pine branch segments, from the OJP-SSA BOREAS site, as simulated by the vectorization method.

were launched from the focal point of a fish-eye lens. Since an 8 mm Nikkor lens provides an image with a near-perfect equi-angular projection, no lens correction was required. This facilitated the calculation of zenith and azimuth angles for the directional vector of each pixel in the scene. Each pixel was directly associated to a modeled ray. Another geometric input, tree height, was estimated from DBH based on allometry (e.g., Figure 1). The final input was the canopy material distribution represented as 3-D cells. The material density for each cell was determined from the vectorization data. Only one vectorized tree, one which was typical for each species at the selected site, was used to simulate all the crowns within the photographs. While this simplifying assumption may not hold for many natural canopies, the selected BOREAS sites had relatively uniform tree crowns. The reconstructed trees were placed in the simulated stand with a random azimuth direction in order to increase the realism of the modeled photographs.

For each ray launched by the model, the probability of a canopy gap was calculated, as described in detail by *Fournier et al.* [1996]. To do this, the probability of transmission through each cell encountered along the path was determined according to the total probability of transmission (P_{gap}). P_{gap} was, in turn, calculated as the product of the transmission probabilities for all cells encountered:

$$P_{\text{gap}} = \prod e^{-[DSG]} \tag{1}$$

where D is the cell density, S is the path length within the cell, and G is the mean projection coefficient factor [*Chen and Black*, 1992]. The rays were tested for intersection with the tree trunks, which were modeled as opaque cones.

Equation (1) assigns a probability of transmission to each pixel in the hemispherical simulation. Each pixel of the probability images represents the probability of a gap. The calculated P_{gap} value, between 0 and 1, is rescaled between 0 and 255 for an 8 bit image. This probability is then translated into an obstruction (0) or a gap (1) event, based on a random number generator applied to the gap probability. Therefore two types of simulated images were generated: the probability distribution and the binary gap images. The resulting binary gap images simulate in situ hemispherical photographs that have been classified using a radiometric threshold (Figure 3). Simulated photographs were calculated for zenith angles and image dimensions that matched the in situ hemispherical photograph. However, the extent of the mapped area around each photograph position is a constraint. Given that the exact tree location is unimportant for crowns at a distance larger than 20 m from the photograph position, for greater realism, we decided to simulate trees for an area exceeding the boundaries of the mapped plot by at least 80 m in each direction. These tree positions were calculated based on the statistics from the mapped plot. The extra trees impacted mainly on the large zenith angles. Simulation of each hemispherical image required approximately 7 hours of calculation on a Pentium 133 MHz computer. This time depended mainly on the number of cells that comprised the simulated tree crown, the number of tree crowns in the plot, and the image dimension.

3.3. Results of the Hemispherical Photograph Simulation

Hemispherical photographs were simulated for the OJP-SSA site at every 10 m on a line going through the center of the mapped plot and at a camera height of 1.5 m. The simulated hemispherical photographs displayed a coarser texture of canopy gaps than did the in situ photographs for the same locations. Figure 3 shows an example of a pair of in situ and simulated hemispherical photographs taken in the center of the mapped plot. A threshold value of 120 (out of 256 gray levels) was applied to all photographs to differentiate foliage from canopy openings. The comparison between in situ and simulated hemispherical photographs for the OJP-SSA BOREAS site suggests a good visual representation of the detailed 3-D canopy material distribution from the vectorization data set. For a more formal validation, the gap fraction for 10 pairs of simulated and in situ photographs were compared for zenith angle rings from 0° to 85° by increments of 5° (e.g., Figure 4). The variability of the gap fraction with zenith angle, for the 10 photograph pairs, is given by Figure 5, where the average gap values and the associated standard error of the simulated photographs is shown as a square point and a standard error bar. All gap fraction values of the in situ photographs are shown with a straight or dotted line.

Comparison between pairs of simulated and in situ photographs typically shows poor correspondence between 0° and 20°, followed by a similar curve shape and values between 25°

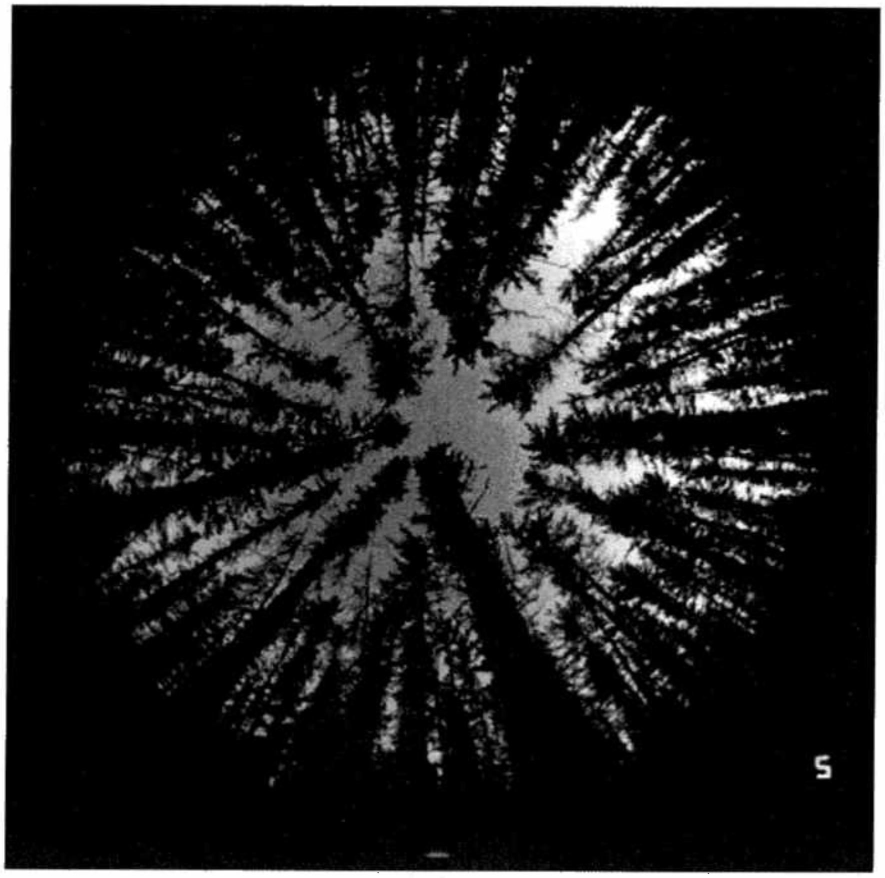

Figure 3a. In situ hemispherical photograph.

and 70°, and ending by discrepancies due to the edge of the simulated stand for zenith angles larger than 70°. The middle portion of zenith angles (25°–70°) is usually very similar (i.e., gap fraction differing by less than 10%). However, larger discrepancies do occur but only for a short range, i.e., for 5°–15°, of zenith angles. The average values of gap fraction of all simulated photographs in Figure 5, although similar in trend to those of the in situ photographs, tend to have larger values for the zenith angle range between 20° and 40°. The differences in gap fraction values are primarily due to seven factors: (1) natural variation among trees, which is not taken into consideration by the model because it uses only one characteristic tree geometry; (2) the significant number of dead branches and shoots under the live crown, which was not simulated; (3) the noninclusion of dead trees in the simulated photographs; (4) classification errors introduced when using a threshold to distinguish foliage and canopy openings for the in situ photographs; (5) small errors in tree positioning; (6) errors inherent to the allometric estimation of height from the DBH; and (7) errors in the viewing configuration of the hemispherical camera system. These factors, in particular, factors 1, 2, 3, and 5, generate large errors for small zenith angles (i.e., smaller than 20°). Considering that small errors lead to large discrepancies between simulated and in situ photographs, it is not practical to reduce the differences of gap fraction values for low zenith angles by means of better representation of material distribution. The decrease of difference in gap fraction at greater zenith angles is due to the fact that error in the estimated distribution of material averages out over the longer path lengths through the canopy. Beyond a limiting zenith angle, typically, about 70°, light obstruction by canopy material is almost complete, and little can be inferred about canopy architecture. This limiting angle is typically determined by the ray path which has a high probability of encountering several crowns.

4. Discussion

The hierarchical method for characterization of canopy architecture was originally tested with success [*Fournier et al.*, 1996] in a plantation forest at the Petawawa National Forest Institute (PNFI; latitude 46.01°W, longitude 77.43°N). By contrast, the BOREAS sites provided a good environment to further test the method in a naturally grown stand. The foliage on the tree crowns at the OJP-SSA site was typically very compact with very limited horizontal extent (e.g., Figure 2). Moreover, the branching pattern of these jack pines was highly irregular. These architectural trends were also observed in the northern study area (NSA) OJP sites as well as in mature (old) black spruce sites of the BOREAS study. Nevertheless the northern sites were less productive. A comparison of jack pine trees of similar heights between the OJP-SSA and PNFI sites shows large differences in material surface and branch volume (Table 4). Even though both sites had similar stand density, the harsher boreal environment results in lower annual tree growth. Moreover, the allometric relationships between tree height and DBH were similar between the two sites even though there was a significant difference in average tree age. These considerations impact on the foliage distribution, the foliage and branching surface, and the crown volume, which in

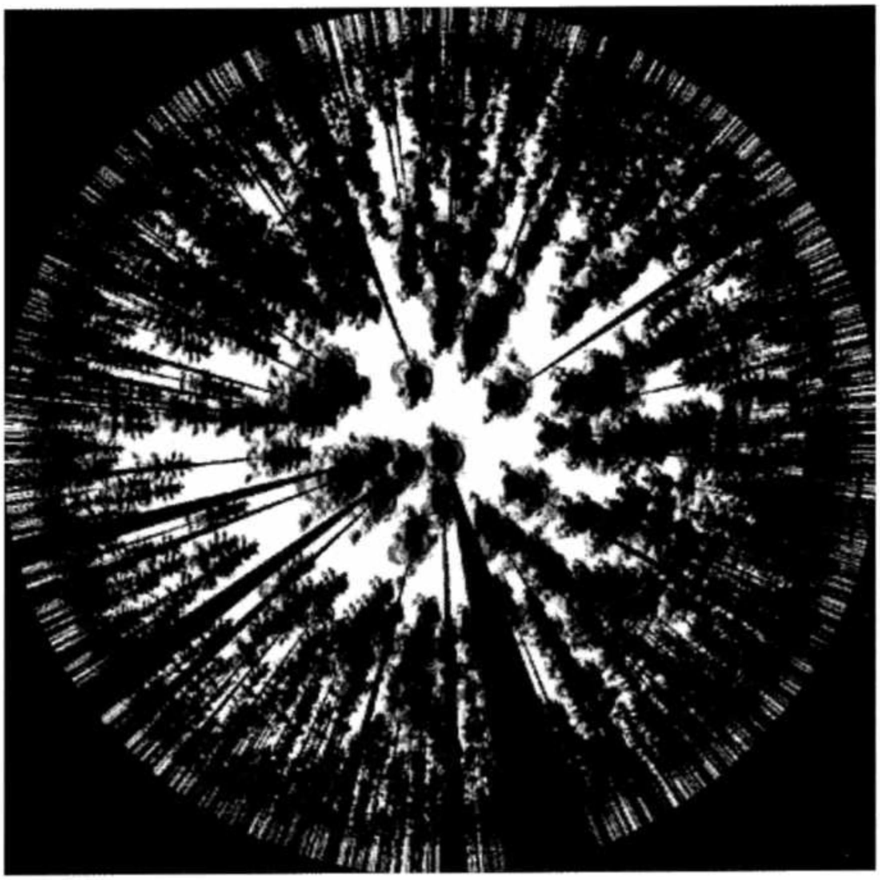

Figure 3b. Simulated hemispherical photograph for the OJP-SSA BOREAS site.

turn, impact strongly on the gap patterns within the canopy. Information acquired with the hierarchical method is suited to quantify differences between forest sites.

The comparison of the percentage of light transmission (gap fraction) from a simulated and an in situ hemispherical photograph (Figure 5) suggests that the ray tracing model was successful at replicating subtle canopy gap patterns. However, we wish to emphasize five points which arise from this modeling effort. First, the compactness of foliage on the branch of the boreal jack pine raises some questions about the necessity of replicating the detailed 3-D structure of the branch segments and foliage. A coarser representation, composed of the general branch position on the trunk and a good estimate of its total material surface, would probably be sufficient for the satisfactory simulation of canopy gaps. Second, the codominant tree only was used to simulate all the trees in the stand, as it was judged to be the most representative in terms of dimension and structure. However, differences in crown volume suggest that three classes of tree should be identified for simulation: dominant/tall, codominant/average height, and suppressed/small. Third, when gap textures were visually compared between the simulated and the in situ photographs, simulated photographs lacked dead branches emanating from the trunk. While these branch segments have been shown to play a minor role in dense canopy [*Fournier et al.*, 1996], their contribution cannot be ignored in a boreal conifer stand. Fourth, the 50 × 60 m mapped plot was an insufficient stand area for the simulation of a complete fish-eye photograph (8 mm lens). Realistic gap textures can be simulated properly only for a zenith angle up to 50° when the mapped plot information is used with the camera at the center of the plot. Significant discrepancies in gap fraction are observed on the simulated photographs for large zenith angles. The simulated stand appears to be surrounded by a clearcut. Consequently, a more complete modeling of the hemispherical photographs, at several positions on the mapped plot, required an extended simulated stand exceeding the mapped plot dimension. Thus tree location and DBH were simulated for an extended area around the mapped plot. This was equivalent to a stand 160 m × 160 m in dimensions. However, this point has a limited impact, since it affects solely the large zenith angles of the simulated photograph.

In summary, simulated photographs faithfully reproduce canopy geometry visible for in situ hemispherical photographs, in particular, for gap fraction analysis for the middle ranges of zenith angles (20°–70°). Moreover, the differences in gap fraction for this middle portion of zenith angle appear insensitive to exact mapping of the stand. The ray tracing model successfully integrates the data gathered at the stand and tree levels to provide a detailed understanding of canopy architecture. In addition, the methodology provides a powerful tool for the simulation of the light regime anywhere in the canopy.

When planning field work to study the ecophysiological processes or the canopy interaction with incoming radiation, a sound site characterization strategy is essential to the analysis. In particular, the successful interpretation of remote sensing measurements often rests on realistic representations of canopy architecture. We suggest that, even though the site description methods are diverse, the basic premise of a hierarchy for spatial information should be mandatory for all site char-

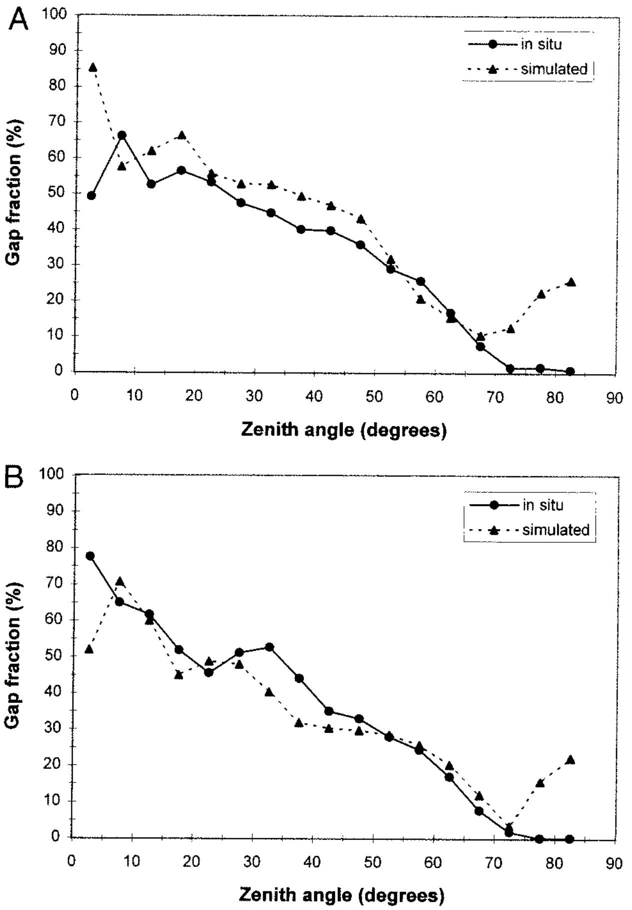

Figure 4. The gap fraction or fraction of light transmitted for two pairs of simulated and in situ hemispherical photographs for 5° rings of zenith angles (a) at position 150, 0 within the mapped plot and (b) at position 110, 0 outside of the mapped plot.

acterization. Our hierarchical characterization method has two advantages. First, it involves explicit identification of the key canopy descriptors at all scales, and second, it provides an effective and adaptable data acquisition sequence to characterize canopy architecture. Hierarchical characterization of canopy architecture provides a sound information base from which to describe these forests and permit comparison of different sites. The methodology permits validation of modeling efforts for scales ranging from the regional level down to the tree level.

5. Conclusion

Ecophysiology and population processes are dynamically tied to canopy architecture. Remotely sensed information concerning forest canopies, together with suitable ground truth data sets, provide a valuable tool for inferring this architecture. Assessment of ecological processes relies, first, on the ability to measure patterns of canopy architecture at an appropriate scale and, second, on an understanding of the relationships between patterns of canopy architecture and driving biophysical processes. The practical constraints inherent to measurements of detailed architecture in forest canopies present a formidable challenge. We propose a four-tiered approach to address this challenge: (1) gathering key climatological and ecological information at the regional scale, (2) mapping the locations of individual trees and understory cover, (3) sampling the 3-D geometry and distribution of leaves and branches within individual tree crowns, and (4) acquiring a catalog of hemispherical photographs that enables detailed analysis of canopy geometry. The effectiveness of this hierarchical characterization method was validated, and demonstrated to be well adapted for boreal ecosystems, by comparison of simulated and in situ hemispherical photographs. For the BOREAS project, our comprehensive measurements of canopy architecture provide investigators with a common ground truth data-

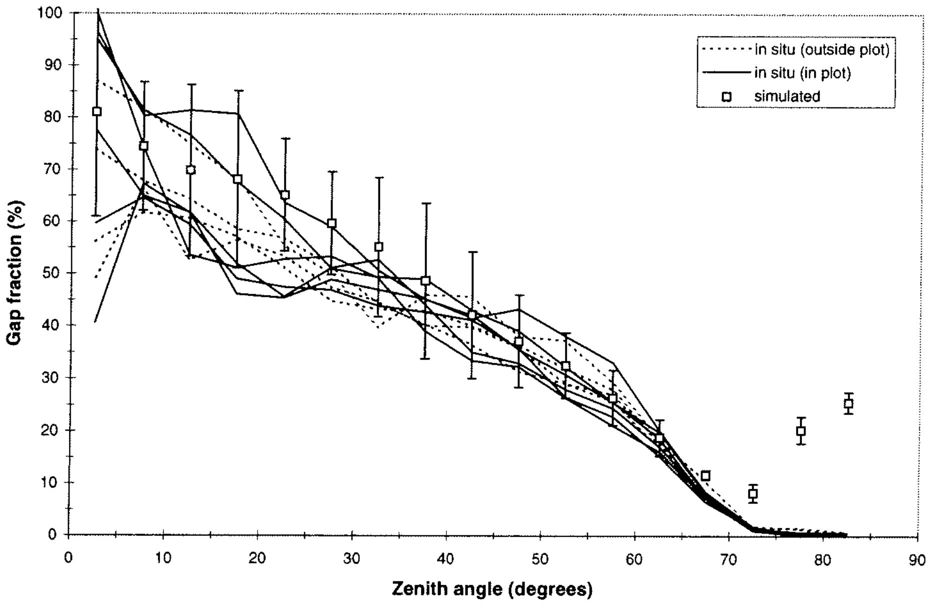

Figure 5. A comparison of gap fraction values with zenith angles obtained for the simulated and in situ hemispherical photographs. Six photographs were taken within the plot boundary (straight lines) and four outside (dotted lines). The average values and the standard deviation (containing 68.3% of data points) of the 10 corresponding simulated photographs are shown with square points and error bars.

Table 4. Comparison Between a Vectorized Jack Pine Tree at the PNFI and Three Vectorized Trees From the OJP-SSA BOREAS Site

Site	Age, years	Height, m	DBH, mm	Stand Density, stem/ha	Live Crown Volume, m^3	Foliage Surface, m^2	Branch Segment Surface, m^2	Height Allometric Equation	
								Slope	Intercept
PNFI	26	15.2	151	1075	40.35	119.47	18.81	0.46	6.98
OJP-SSA	84	15.9	179	1082	23.41	76.61	13.64	0.47	7.88
OJP-SSA	64	13.4	125	1082	13.00	38.15	7.69	0.47	7.88
OJP-SSA	72	13.75	104	1082	3.87	18.87	4.29	0.47	7.88

PNFI, Petawawa National Forest Institute; OJP-SSA, old jack pine–southern study area; DBH, diameter at breast height.

base for all major sites. Our hierarchical data acquisition approach, enabling detailed characterization of canopy architecture, constitutes a solid basis with which to link remotely sensed patterns and ecological processes from leaf to regional levels.

Acknowledgments. We thank Jing Chen, Yvette Alger, Venessa Peterson, Nicole August, and Robert Gauthier for assistance and scientific discussion concerning this project. This work was supported by the Canada Centre for Remote Sensing, the Kansas Applied Remote Sensing Program, the Kansas Biological Survey, the Kansas Center for Computer Aided Systems Engineering, NASA grant NAG5-2358, and the University of Kansas Research Development and General Research Funds.

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(Received July 15, 1996; revised September 9, 1996;
accepted December 12, 1996.)