

Characterization of radiation regimes in nonrandom forest canopies: theory, measurements, and a simplified modeling approach

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Summary We used field measurements and Monte Carlo simulations of canopy gap-size distribution and gap fraction to examine how beam radiation interacts with clumped boreal forest canopies of aspen (*Populus tremuloides* Michx.), black spruce (*Picea mariana* (Mill.) B.S.P.) and jack pine (*Pinus banksiana* Lamb.). We demonstrate that the Beer-Lambert law can be modified to accommodate transmission of radiation through a clumped forest canopy as a function of path length or sun zenith angle. Multiband Vegetation Imager (MVI) measurements and Monte Carlo simulations showed that values of the zenith element clumping index ($\Omega_e(0)$) are typically between 0.4 and 0.5 in jack pine and black spruce and 0.65 in aspen. Estimates of LAI obtained from MVI measurements of the canopy gap fraction and adjusted for canopy clumping and branch architecture yielded LAI values of 3.0 in jack pine, 3.3 in aspen, and about 6.0 in black spruce. These LAI estimates were within 10–25% of direct measurements made at the same sites. Data obtained with the MVI, along with numerical simulations, demonstrated that assumptions of random foliage distributions in boreal forests are invalid and could yield erroneous values of LAI measured by indirect techniques and false characterizations of atmosphere–biosphere interactions. Monte Carlo simulations were used to develop a general equation for beam radiation penetration as a function of zenith angle in clumped canopies. The essential measurements included stem spacing, crown diameter, crown depth, and within-crown gap fraction.

Keywords: canopy gap-size distribution, canopy nonrandomness, clumping index, multiband vegetation imager, radiation regime.

Introduction

Typically, simplified scaling approaches are used to derive values of canopy photosynthesis from leaf-level measurements of CO₂ exchange (Norman 1993). To make use of scaling techniques, the interaction between radiation and vegetation needs to be characterized. To quantify the exchange of H₂O, CO₂ and heat between the biosphere and atmosphere, careful parameterization of the radiation regime in the ecosystem is essential. Furthermore, modeling studies require proper definitions of canopy architecture to portray accurately the trans-

mission of radiation from the top of the canopy to the soil surface. Forests generally have a high degree of natural variability, and typically have distinct levels of organization that cause foliage to be grouped or clumped as a consequence. The challenge is to obtain an adequate quantitative description of the role of canopy architecture in radiation exchange with a tractable amount of required input data and a simple model. Past approaches have used elaborate three-dimensional type models (Fournier et al. 1996).

We have attempted to resolve a major difficulty associated with modeling and scaling leaf photosynthesis in coniferous forests by developing a procedure to accommodate canopies with foliage clumped at several levels of organization. The procedure involves a modification of the radiation extinction based on a random distribution of foliage elements to account for foliage clumping. The phenomenon of foliage clumping influences the accuracy of indirect leaf area index values derived from radiation penetration (gap-fraction) measurements, characterization of the within-canopy radiation regime, and estimates of carbon uptake based on simple scaling procedures or soil–plant–atmosphere models. Leaf area index is one of the primary measures used to characterize plant canopies (Bonan 1993). In forest studies, indirect measurements of LAI are preferred to direct, destructive sampling techniques because of the time and labor associated with harvesting trees. Indirect measurements of LAI can be obtained quickly in many forests (see review by Welles 1990); however, these methods use the Beer-Lambert law to invert a value of LAI based on the assumption of a random distribution of foliage elements (Nilson 1971, Ross 1981). Therefore, these indirect LAI values need to be adjusted for nonrandomness using correction factors ($\Omega_e(\theta)$) that account for foliage clumping at scales larger than shoots or leaves (Chen et al. 1997, Kucharik et al. 1997), and for within-shoot clumping of needles (Oker-Blom and Smolander 1988, Fassnacht et al. 1994, Stenberg et al. 1994, Chen et al. 1997).

Data obtained with the Multiband Vegetation Imager (MVI, Kucharik et al. 1997, 1998) indicate that canopy nonrandomness correction factors, which are based on measurements of canopy gap-size distribution (Chen and Cihlar 1995), are dependent on zenith angle in the canopy (Chen 1996, Kucharik et al. 1997). Nilson (1971) first described a canopy clumping index (Ω); however, an angular dependence was not specified.

Kucharik et al. (1997) showed that the product of LAI and $\Omega_c(\theta)$ can be used to estimate sunlit LAI, or the interception of direct beam radiation, using the Beer-Lambert law. In this paper we show that Beer's law can be adjusted and used to characterize radiation interception in nonrandom forests. The dependence of clumping index on zenith angle is essential for describing the transmission of direct beam radiation in clumped forest canopies.

We used measurements of $\Omega_c(\theta)$, indirect LAI and total LAI for three boreal forest species: jack pine (*Pinus banksiana* Lamb.), black spruce (*Picea mariana* (Mill.) B.S.P.), and aspen (*Populus tremuloides* Michx.), and the results of Monte Carlo simulations for the three boreal species, along with other types of canopy architecture, for three purposes. First, to evaluate indirect measurements of LAI and $\Omega_c(\theta)$ in boreal conifers using the MVI, and to correct for element clumping, within-shoot clumping of needles, and woody interception of light to obtain adjusted indirect LAI values for comparison with direct LAI measurements; second, to describe the transmission of beam radiation as a function of zenith angle based on MVI measurements and Monte Carlo simulations; and third, to outline an approach to estimate $\Omega_c(\theta)$ without prior knowledge of canopy gap-size distribution, which can be difficult to measure.

Gap fraction theory

Most instruments that measure the canopy gap fraction as a function of angle (e.g., LAI-2000, Li-Cor, Inc., Lincoln, NE, DEMON, Assembled Electronics, Yagoona, NSW, Australia, Ceptometer, Decagon Devices, Inc., Pullman, WA; Welles 1990, Welles and Cohen 1996) use a Poisson model to infer values of LAI indirectly. The probability $P(\theta)$ of a direct beam penetrating a plant canopy at a zenith angle of θ , assuming azimuthal symmetry, can be described by:

$$P(\theta) = \exp[-K(\theta)\Omega(\theta)L_t/\cos(\theta)], \quad (1)$$

where $K(\theta)$ is the fraction of foliage projected in direction θ , $\Omega(\theta)$ is the total foliage clumping factor, and L_t is a vegetation area index defined as half the total surface area (leaves, stems, and branches) per unit ground surface area (Chen and Black 1992). Instruments such as the MVI, LAI-2000, DEMON, and hemispherical photography (Rich 1990), which have the ability to measure the canopy gap fraction ($P(\theta)$) over a range of zenith angles, derive an estimate of $\Omega(\theta)L_t$, referred to as "effective LAI" or L_e (Chen et al. 1991). Thus, some knowledge about the spatial arrangement of foliage elements in clumped forest canopies is essential to estimate LAI accurately on the basis of indirect measurements. Furthermore, non-leafy tissues (stems and branches) that intercept incoming radiation are also included in the value of L_e . Because L_e is associated with measurements of the canopy gap fraction at different view angles, the quantity is referred to here as $L_e(\theta)$.

The definition and measurement of $\Omega(\theta)$ in conifer forests are complicated because up to four levels of clumping may be present as a result of grouping at the shoot, branch, whorl, and tree crown levels (Norman and Jarvis 1974). Even if conifer

shoots, which are taken as the primary foliage elements, are randomly distributed throughout a canopy, the tight packing of needles on an individual shoot results in mutual shading of needles (clumping), causing optical techniques to underestimate total needle surface area. Chen and Cihlar (1995) show that:

$$\Omega(\theta) = \frac{\Omega_c(\theta)}{\gamma_e}, \quad (2)$$

where γ_e is needle-to-shoot area ratio (1/2 the needle surface area to 1/2 total shoot-envelope surface area), which characterizes the amount of clumping that occurs within a typical shoot, and $\Omega_c(\theta)$ is the element clumping index quantifying the effect of foliage clumping at scales larger than individual leaves or shoots. Values of γ_e and other definitions of the amount of needle clumping on shoots have been discussed (Oker-Blom and Smolander 1988, Deblonde et al. 1994, Fassnacht et al. 1994, Chen 1996, Chen et al. 1997). However, there is still considerable confusion about the numerical definition of needle clumping. The value of $\Omega_c(\theta)$ that is estimated from MVI or TRAC (Tracing Radiation and Architecture of Canopies) measurements only includes clumping at scales larger than the mean element size (shoots or leaves). The MVI is unable to characterize within-shoot clumping in conifers because individual needles and gaps between needles (less than a few millimeters in some cases) are often smaller than an MVI image pixel. Therefore, the needle area of a shoot is not accurately measured as part of the gap-size distribution that is used to derive values of $\Omega_c(\theta)$. If shoots are randomly distributed in a canopy, then $\Omega_c(\theta) = 1$, and γ_e would account for the only existing level of clumping. However, because conifer canopies usually demonstrate higher orders of organization, shoots are usually not randomly positioned. Therefore, values of $\Omega_c(\theta)$ are essential for characterizing radiation penetration in forests exhibiting clumped foliage.

We have used the approach of Chen (1996), which is almost identical to the theory developed by Fassnacht et al. (1994), as the basis for defining γ_e . We used values of γ_e measured by Chen et al. (1997) in jack pine and black spruce stands. The procedure developed by Kucharik et al. (1998) was used to adjust indirect measurements of LAI obtained with the MVI to account for foliage clumping and light-intercepting branch hemi-surface area. Branch architecture values reported for aspen, black spruce, and jack pine by Kucharik et al. (1998) were used to calculate total LAI.

Measurements, simulations and results

Data were obtained during the BOREAS (Boreal Ecosystem-Atmosphere Study) field campaigns of 1994-1996. Measurements of $L_e(\theta)$ and the zenith element clumping index $\Omega_c(\theta)$ were made with the MVI, and destructive measurements were made by Gower et al. (1997) to estimate total LAI in forest stands in the Northern Study Area (NSA) near Thompson, Manitoba, and in the Southern Study Area (SSA) near Prince Albert, Saskatchewan during early August 1994. Forty MVI image pairs were taken along Transect B at the SSA old aspen

(OA) site on July 14, 1996, covering the first 100 m to the SW of the micrometeorological flux tower, spaced 3 m apart. Approximately 50 MVI image pairs were taken at the NSA old jack pine (OJP) site during July 26–29, 1994. Most image pairs were analyzed from portions of the intensive study plot TE-23 (terrestrial ecology group 23), with the composite of MVI images covering approximately 1000 m² of ground area. On July 8–9, 1996, 35 image pairs were collected at the SSA old black spruce (OBS) forest site along Transect B, at distances between 45 and 125 m from the micrometeorological flux tower spaced 2–3 m apart. An additional 30 image pairs were analyzed from two plots (TE-6) with distinctly different stand densities than the region located along Transect B. The 15 image pairs obtained in each TE-6 plot were generally sufficient to photograph the entire crown area above each plot.

MVI measurements of $L_e(\theta)$

The MVI measurements of $L_e(\theta)$ are summarized in Table 1 and Figures 1 and 2. Figure 1 shows a composite graph of all $L_e(\theta)$ measurements made with the MVI pointed toward the canopy zenith and the corresponding value of $\Omega_e(0)$ calculated for each processed MVI image pair. For comparison with the boreal species, MVI data from an oak forest (LAI = 4) in North Carolina and a sugar maple (LAI = 6) stand in Wisconsin during late August 1996 are plotted in Figure 1 as examples of full-cover deciduous canopies. Each MVI measurement represents architectural data from a 5×10 m canopy area in aspen, oak, and sugar maple stands and an approximately 3.5×7 m canopy area in black spruce and jack pine stands. Mean values of $L_e(\theta)$ were 1.16 ± 0.70 for the NSA-OJP lot (TE-23), and from 1.4 to 2.2 at SSA-OBS (Table 1). The variation in stand density and corresponding high frequency of large between-crown gap sizes within the black spruce stand account for the wide range of indirect LAI values measured with the MVI toward the zenith. At the SSA-OA site, mean $L_e(\theta)$ was 2.18 ± 0.39 . The smaller standard deviation in aspen than in jack pine

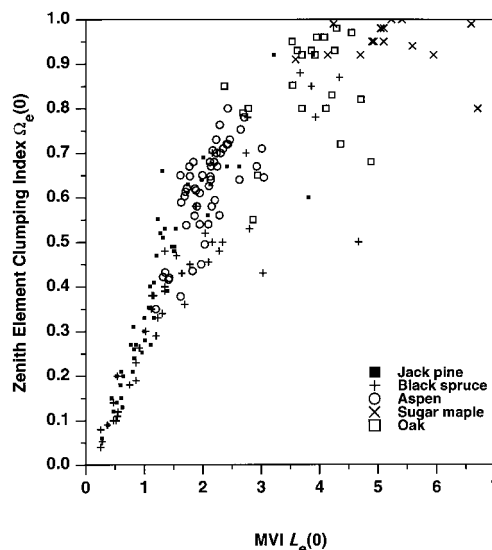


Figure 1. MVI estimates of indirect LAI measured toward the canopy zenith ($L_e(\theta)$) and corresponding estimates of the element clumping index ($\Omega_e(0)$) for jack pine, black spruce, aspen, sugar maple and oak.

or black spruce suggests less variation in stem density. To ensure that a good spatial representation of the LAI in a conifer stand is obtained with the MVI, more point measurements need to be collected than with other gap fraction instrumentation, such as the LAI-2000, which typically measures a larger field of view (FOV). The complexity of conifer forest ecosystems partially explains the large variation in indirect LAI values obtained with the MVI. Measurements of total gap fraction probably have a higher degree of uncertainty for conifers than for deciduous species because the large number of small between-needle gaps, which are typically millimeters to a few centimeters in size, are difficult to detect. This problem is of particular concern in canopies with LAI > 5, where

Table 1. Composite table of architectural data for SSA-OBS, NSA-OJP and SSA-OA sites. Values are means with standard deviations in parentheses. Abbreviations: $L_e(\theta)$ is the indirect LAI measured with the LAI-2000; $L_{e,leaf}$ is the portion of $L_e(\theta)$ that is just leaves (corrected for branch area; see Kucharik et al. 1998); $L_{scale,MVI}$ is the LAI estimated from the MVI gap fraction measurements and corrected for branch area and canopy nonrandomness; L_{tot} is the direct estimate of total LAI derived from allometric equations (Gower et al. 1997); and % diff is the difference between $L_{scale,MVI}$ and L_{tot} .

Value	SSA-OA Transect B	SSA-OA Plot 4	NSA-OJP TE-23 Plot	SSA-OBS Transect B	SSA-OBS Plot 1	SSA-OBS Plot 3
$L_e(\theta)$ (MVI)	2.18 (0.39)	1.85 (0.22)	1.16 (0.70)	1.64 (1.29)	2.2 (0.94)	1.4 (1.1)
$\Omega_e(0)$ (MVI)	0.64 (0.10)	0.64 (0.06)	0.45 (0.19)	0.35 (0.28)	0.49 (0.19)	0.38 (0.28)
$\Omega_e(0)/\gamma_e$	0.64	0.64	0.36	0.26	0.36	0.28
$L_e(\theta)$ (LAI-2000)	2.3	—	1.6	2.45	2.7	1.73
$\Omega_e(\theta)^1$ (TRAC)	0.72	—	0.82	0.70	—	—
$L_{e,leaf}$ (MVI)	2.15	1.82	1.10	1.60	2.15	1.36
γ_e	1.00	1.00	1.25	1.36	1.36	1.36
$L_{scale,MVI}$	3.36	2.85	3.05	6.22	5.96	4.86
L_{tot} (allometry) ²	3.3	2.80	2.2	5.60	7.93	4.4
% diff	+2	+2	+39	+11	-25	+10

¹ Values reported by Chen et al. (1997).

² From Gower et al. (1997).

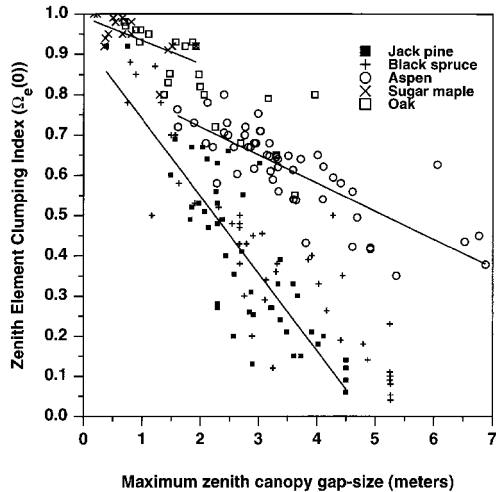


Figure 2. MVI measurements of the maximum zenith canopy gap size (m) plotted against the zenith value of the element clumping index for jack pine, black spruce, aspen, sugar maple, and oak. Separate best-fit lines are plotted for conifers, aspen, and oak and sugar maple.

small errors in detection of the total gap fraction can lead to large uncertainties in LAI.

MVI estimates of $\Omega_e(0)$

When conifer stands are viewed from the near vertical direction (zenith), crowns can appear as almost solid geometric objects with large gaps (2 to > 6 m, Figure 2) between individual crowns. Because the MVI is used as a zenith-pointing instrument, it is sensitive to these large between-crown gap sizes and their frequency as well as to the relatively small number of within-crown gaps. The ratio of within-crown gap fraction to total gap fraction is small in deciduous canopies located south of the boreal region because many deciduous species exhibit almost full canopy closure (e.g., sugar maple, oak). Some deciduous canopies appear as one solid volume of nearly randomly distributed foliage. However, in deciduous aspen located within the boreal forest region, overlapping crowns in the zenith direction do not occur; therefore, canopy clumping must also be accounted for.

The MVI measurements of zenith canopy gap-size distribution showed that 80–95% of the total zenith gap fraction at NSA-OJP and SSA-OBS is comprised of between-crown gaps, whereas this fraction was about 40–60% in aspen. Figure 2 illustrates that the relationship between maximum zenith gap-size (related to tree spacing) and $\Omega_e(0)$ is dependent on species. In aspen, maximum zenith gap-sizes of 2–4 m are common, and lead to $\Omega_e(0)$ values of between 0.6 and 0.75. For the same range of maximum gap-sizes in conifer stands, values of $\Omega_e(0)$ are typically 0.2–0.5 (Figure 2). The difference in $\Omega_e(0)$ for similar maximum gap-sizes occurs because the ratio of between-crown gap fraction (horizontally projected) to total gap fraction is much greater in conifers than in aspen. Calculation of $\Omega_e(0)$ (Chen and Cihlar 1995) is based on the difference between initial and final gap fractions: the final gap fraction is obtained after removal of gaps that cause the gap-size distribu-

tion to depart from the theoretical random distribution. Usually the largest gaps are removed, corresponding primarily to the between-crown gap sizes in this study. As a result, the larger the difference between initial and final gap fractions, the lower the value of $\Omega_e(0)$. Consequently, $\Omega_e(0)$ in aspen is larger than in black spruce or jack pine, even though between-crown gap-sizes in the zenith view direction may be comparable.

Maximum zenith gap-size provides information about why the effect of zenith angle on gap-size distribution leads to differences in element clumping indices derived from MVI and TRAC (Chen and Cihlar 1995) measurements. The TRAC was used during BOREAS to measure the sunfleck size distribution beneath forest canopies at solar zenith angles between 30 and 70°. Table 1 shows that MVI values of $\Omega_e(0)$ and reported values of $\Omega_e(\theta)$ measured with TRAC (Chen et al. 1997) differed by only about 10–15% in aspen. In contrast, MVI values of $\Omega_e(0)$ at NSA-OJP and SSA-OBS are approximately equal to 0.4, with a range from 0.1 to 0.9 (Figure 1), whereas TRAC measurements give $\Omega_e(\theta)$ values of 0.7–0.8 (Chen 1996). Sample gap-size distributions for MVI image locations plotted in Figures 3a and 3b show the heterogeneity and site variability that exist in jack pine and black spruce stands. Therefore, numerous MVI image pairs are needed to provide a good spatial representation of these forests. Maximum gap sizes measured with TRAC at SSA-OBS and NSA-OJP were 0.9–2.0 m (Chen and Cihlar 1995). In the same forest stands, maximum gap-sizes measured with TRAC at solar zenith angles of 30–70° were generally at least a factor of two lower than maximum gap sizes measured toward the zenith with MVI. Differences in maximum gap sizes and gap-size distributions in conifers obtained at different measurement angles demonstrate that canopy gap-size distribution is dependent on zenith angle.

Monte Carlo simulations of nonrandom forest architecture

Monte Carlo simulations of forest canopy architecture and characteristic stem densities were performed to elucidate the divergence in $\Omega_e(\theta)$ measurements made at various zenith angles with TRAC and MVI. A complete description of the Monte Carlo model is given by Kucharik et al. (1997). The values of stem densities, crown dimensions (diameter and depth) and LAI used as inputs are shown in Table 2. In our Monte Carlo simulations of conifer stand architecture, crown volumes are shaped as prolate spheroids (vertical “cigar” shapes) or spheres. Individual shoots representing photosynthetically active foliage are placed randomly within the volume of each crown, assuming azimuthal symmetry and a spherical leaf angle distribution.

Studies of canopy gap-size distribution and calculated values of $\Omega_e(\theta)$ show that, as the zenith angle approaches 90° (horizontal view or sun at horizon), the canopy element clumping factor increases toward unity, suggesting that the canopy appears as a random distribution of foliage elements. A numerical simulation of black spruce shows that total gap fraction and gap-size distribution differ at zenith angles of 0 and 60° (Figure 4). Between-crown gap sizes that appear larger than 1.5 m at a zenith angle of 0° are nonexistent at a zenith angle of 60°. Additionally, the total gap fraction modeled at a

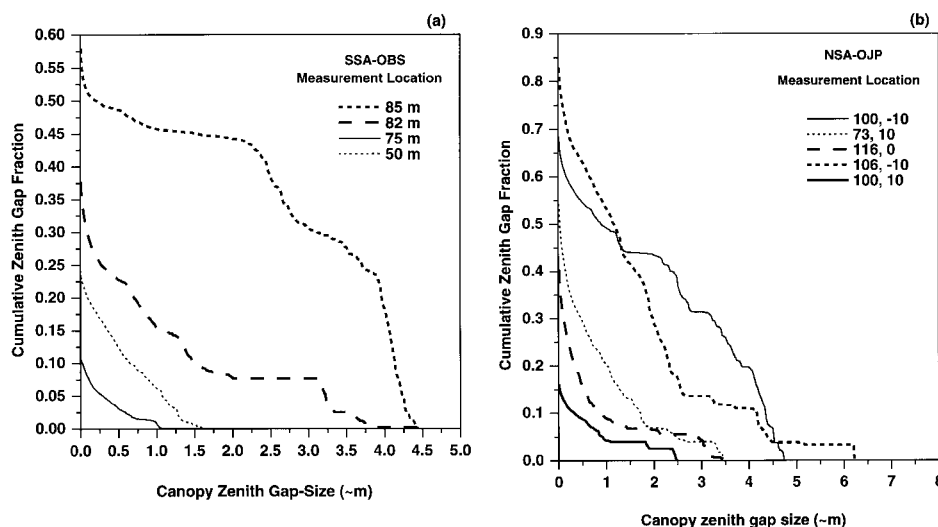


Figure 3. (a) Sample MVI-measured canopy gap-size distributions (toward the zenith) along Transect B at the BOREAS SSA-OBS site on July 8–9, 1996. Numbers associated with each sample distribution denote distance (m) along the transect from the micrometeorological flux tower. (b) Sample MVI-measured canopy gap-size distributions at the BOREAS NSA-OJP site within the study plot of TE-23 on July 26–29, 1994. The number associated with each distribution denotes location (m) within the TE-23 plot.

Table 2. Range of forest canopy structural values used in Monte Carlo simulations of jack pine, black spruce, aspen and other canopy types to derive empirical relationship in Equation 3.

Quantity	Jack pine	Black spruce	Aspen	Other canopies
Stem density (trees ha ⁻¹)	700–4200	1000–5200	700–2400	200–6000
Crown diameter (m)	1.5–3.0	1.3–2.8	2.5–5.0	0.5–9.0
Crown depth (m)	5.0–8.0	5.0–9.0	3.0–6.0	2.0–10.0
LAI	2.0–4.0	3.0–6.0	2.0–4.0	0.5–8.0

zenith angle of 60° is much smaller than that modeled at the canopy zenith (0.16 versus 0.44).

The dependence of $\Omega_c(\theta)$ on θ is plotted in Figure 5 for aspen, oak, sugar maple, jack pine, and black spruce based on Monte Carlo simulations and MVI measurements of $\Omega_c(\theta)$ for each species. Some representative values of $\Omega_c(\theta)$ obtained with TRAC at the BOREAS study sites are plotted for comparison (Chen 1996). The TRAC measurements of $\Omega_c(\theta)$ at zenith angles greater than 50° were slightly lower than the numerically simulated values of $\Omega_c(\theta)$ (Figure 5). In part, the discrepancy is attributable to the limited accuracy with which TRAC characterizes small canopy gaps as a result of the penumbra effect (Miller and Norman 1971). Additionally, branch architecture, which is not accounted for in the Monte Carlo model, may be a source of error in quantifying clumping because branches can influence the spatial distribution of canopy foliage. However, Kucharik et al. (1998) have shown that branches in healthy boreal stands of black spruce, jack pine and aspen are preferentially shaded by other foliage; therefore, the gap-size distribution is not likely to change significantly if branches are removed from the canopy. In defoliated canopies, branches will have a more important effect on canopy gap-size distribution. Our modeling study also suggests that the angle dependence differs with canopy architecture because there is a

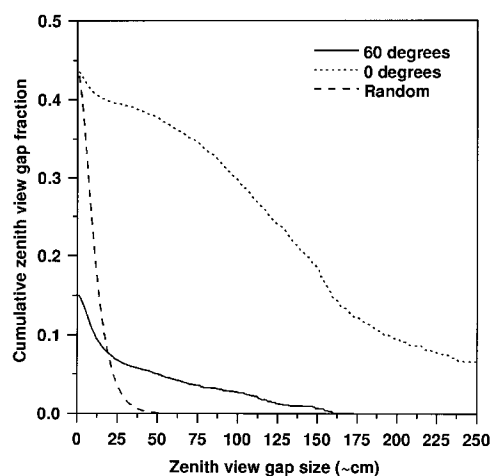


Figure 4. Cumulative gap-size distributions (fraction of gap lengths longer than specified value on the abscissa) of typical boreal jack pine canopy architecture derived from a Monte Carlo model. In this simulation, crown diameter = 2.0 m, LAI = 2.2, stem density = 1700 stems ha⁻¹, and crown depth = 6 m. Modeled distributions are compared for zenith angles of 0 and 60°. A corresponding random gap-size distribution for the zenith view of the total gap fraction is plotted for comparison.

greater shift in $\Omega_c(\theta)$ at zenith angles between 0 and 50° in conifer canopies than in deciduous canopies.

Comparison of indirect and direct measurements of LAI

We compared direct estimates of LAI in clumped forests with indirect MVI LAI estimates that were corrected for woody area, element clumping (using values of $\Omega_c(0)$), and within-shoot clumping (γ_e). Indirect LAI measurements that were corrected for foliage clumping and light-intercepting branch hemi-surface area made at three locations in the SSA-OA site were within 5% of direct measurements (Table 1). However, indirect LAI measurements have a higher probability of measurement error in conifers than in deciduous species, because conifers have inherently more light-intercepting woody mate-

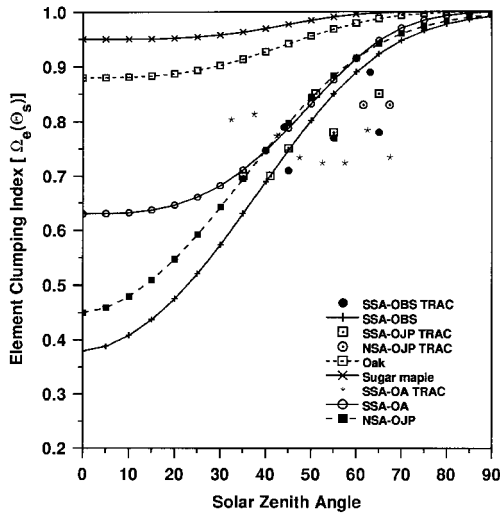


Figure 5. Values of the element clumping index in aspen, black spruce, jack pine, sugar maple, and oak as a function of zenith angle. Values of $\Omega_e(0)$ are MVI measured quantities at each site, and Monte Carlo simulations are used to characterize the angular response according to specific stand architecture of each species. The TRAC measurements for SSA-OA, NSA-OJP, and SSA-OBS are plotted for comparison. The MVI data for oak were obtained in August 1996 at the Duke University research site (North Carolina), and data for sugar maple were obtained in September 1996 near Sayner, WI in the Nicolet National Forest.

rial and two independent clumping indices (element and within-shoot) that can have associated errors of 5–10% each (Chen et al. 1997). Because the MVI is able to measure the contribution of branches to $L_c(\theta)$ (Kucharik et al. 1998), we can minimize this potential source of error. In jack pine and black spruce stands, differences between corrected indirect MVI LAI measurements (based on Equation 9 in Kucharik et al. (1998); referred to hereafter as MVI-optical LAI) and direct LAI estimates were 5–40% (Figure 6). This difference accounts for branches, needle clumping on shoots and shoot or leaf clumping. Because we calculated $\Omega_e(0)$ independently in two plots differing only in stand density at SSA-OBS (Plots 1 and 3; Table 1), we can compare the MVI-optical LAI and direct LAI estimates that were calculated separately for each plot based on the allometric relationship established for the entire stand (Gower et al. 1997). We found that we overestimated direct LAI by 10% (stem density = 2850 stems ha^{-1}) on Plot 3, and underestimated direct LAI by 25% on Plot 1 (stem density = 6650 stems ha^{-1}) (Figure 6). The difference in $\Omega_e(0)$ and $L_c(\theta)$ point-measurement values on Plots 1 and 3 also suggests a high degree of variability within the black spruce stand because the plots are only 200 m apart. Monte Carlo simulations show that MVI is likely to underestimate LAI in forests with extremely dense crowns (high foliage density) such as black spruce (i.e., Plot 1), because the canopy gap-size distribution does not yield enough information to correct for the high degree of foliage clumping. Furthermore, direct LAI values above 6 are more likely to be underestimated because of errors in the detection of the total canopy gap fraction, which can be less than 5% in some canopies. Generally, MVI-

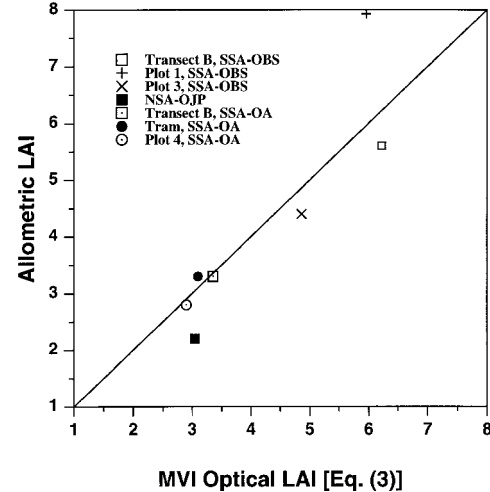


Figure 6. The LAI derived from MVI gap fraction measurements that were corrected for branch area and foliage clumping compared to direct estimates of LAI based on allometric relationships for several locations within SSA-OA, SSA-OBS, and NSA-OJP during BOREAS.

optical LAI averaged 5.7 for black spruce at SSA-OBS. This was only a 2% overestimate compared with a direct LAI of 5.6 measured by Gower et al. (1997) on all four allometric plots. In jack pine, MVI-optical LAI (= 3.1) overestimated direct LAI by 40% at NSA-OJP ($L_{\text{tot}} = 2.2$).

General approach for characterizing the radiation regime in nonrandom canopies

Based on our measurements and Monte Carlo simulations of LAI, $L_c(\theta)$, $\Omega_e(\theta)$ and their relationship to general forest stand structure (stem density, crown diameter, crown depth and foliage density) for a range of forest types (highly clumped conifers to full cover temperate deciduous), we have derived a set of empirical relationships that can be used to estimate $\Omega_e(\theta)$ without having to make gap-size measurements with the TRAC or MVI. The clumping index is a key component for adjusting indirect LAI measurements derived from multi-angular gap fraction measurements made with commercially available instruments such as the LAI-2000, DEMON or Ceptometer (Welles 1990). The clumping index is the factor necessary to make the Beer-Lambert law applicable to forest stands that exhibit nonrandom distributions of foliage. Because foliage clumping in natural forest ecosystems is the norm rather than the exception, mean gap-fraction-versus-angle measurements used to estimate LAI indirectly are not sufficient to characterize clumping. We suggest that the crucial information needed to define a canopy clumping index as a function of angle is contained within simple stand structure variables. These variables include crown diameter and depth, stem density and the canopy gap fraction toward the zenith (within 15°) partitioned into between-crown and within-crown components. Each of these four factors has a specific sensitivity to the general canopy foliage spatial distribution, and together they provide a means of estimating $\Omega_e(\theta)$ without using detailed measurements of canopy gap-size distribution. How-

ever, we note that the most accurate values of $\Omega_c(\theta)$ will be obtained from actual canopy gap-size distribution measurements.

Crown density and diameter provide information about whether canopy closure is attained. These two quantities are related to the fraction of ground area that is covered by crown envelopes (horizontal projections of crown limits) and influence the frequency and size of the largest gaps present in the canopy. The largest gaps generally occur between crowns and are a major cause of the canopy clumping index deviating from unity (random). The vertical extent of foliage in crowns (crown depth) affects radiation transmission at angles off the zenith. Crown depth and crown density determine the angular dependence of the clumping factor $\Omega_c(\theta)$. The within-crown gap fraction (hereafter referred to as crown porosity, Φ) is important because it generally contains small gaps (< 20 cm) that are typical of a random foliage distribution.

We describe our approach in three steps. First, we obtain an estimate of $\Omega_c(0)$ that is dependent on Φ and ground area covered by crown envelopes when viewed from nadir. Second, we determine the maximum possible value of the element clumping index ($\Omega_{e,max}$) (which in most cases will be 1.0). Third, we estimate a single parameter based on crown depth and tree crown diameter that controls the response of $\Omega_c(\theta)$ with angle.

Quantities needed to obtain $\Omega_c(0)$

To estimate $\Omega_c(\theta)$ as a function of zenith angle, the smallest typical value of $\Omega_c(\theta)$, corresponding to the element clumping index value at the canopy zenith ($\Omega_c(0)$), and the largest possible clumping index, occurring at the largest path length through the canopy (sun at the horizon), are determined based on physical dimensions of crowns, and some gap fraction estimates. Because the theory has been verified by MVI measurements, we used estimates of between-crown gap fraction and within-crown gap fraction viewed toward the zenith from beneath the canopy.

Two key quantities are needed to calculate $\Omega_c(0)$: (1) the fraction of ground area covered by the horizontal projection of crown envelopes (f_c) (from nadir view), which is a function of the typical tree crown diameter (D), and the tree stem spacing (λ), or stem density, within a study plot; and (2) an estimate of crown porosity (Φ); this quantity, which is related to foliage density, is defined as the gap fraction within crown envelopes divided by f_c . A series of zenith gap fraction measurements are needed along a transect beneath a canopy to partition the total gap fraction ($f_{gap,t}(0)$) between within-crown and between-crown gaps. The Li-Cor LAI-2000 can be used to make multi-angular gap fraction measurements. Although the LAI-2000 measures transmission at five zenith angles, only data from Ring 1 is used to measure the transmission of radiation at zenith angles from 0 to 15°. To determine $f_{gap,t}(0)$ in a clumped forest with Ring 1 of the LAI-2000, we recommend that a transect length of 100–500 m be used with the frequency of measurements dependent on tree spacing and crown diameter. When the LAI-2000 field of view (FOV) is restricted to a zenith angle of 15°, less canopy area is measured compared

with using the entire 140° FOV of all five rings. Consequently, more measurements are necessary than are usually performed with the LAI-2000 to obtain spatially representative averages. Measurements both between crowns and beneath crowns must be recorded along the transect so that a mean total gap fraction toward the zenith is obtained.

An estimate of the total fraction of ground area covered by the horizontal projection of crown envelopes (f_c) is necessary to partition $f_{gap,t}(0)$ into between-crown and within-crown gaps. If crowns are treated as opaque circular objects, the areal crown cover fraction can be defined as the crown silhouette area per unit ground area, determined by the crown envelope projected onto the horizontal from the zenith direction. To obtain this value of f_c , the typical crown silhouette area (πr_c^2 , where r_c is the crown radius in the horizontal direction) is multiplied by the number of crowns and divided by the total ground unit area on which the stem density is based. If f_c is greater than 1.0, crowns typically overlap in the forest, and the entire value of $f_{gap,t}(0)$ can be defined as within-crown gap fraction ($f_{gap,c}(0)$). The total gap fraction occurring between crowns ($f_{gap,b}(0)$) can be estimated by $1 - f_c$, and $f_{gap,c}(0)$ is therefore approximated by $f_{gap,t}(0) - f_{gap,b}(0)$. If the value of $f_{gap,c}(0)$ is < 0, it can be assigned a value of 0 for all practical purposes. Crown porosity (Φ) is determined by dividing $f_{gap,c}(0)$ by f_c ($\Phi = f_{gap,c}(0)/f_c$). The value of Φ may be described as a normalized within-crown gap fraction. Table 3 shows the results of Monte Carlo simulations for aspen, black spruce and jack pine canopies, ranging in LAI from 2 to 6 (15 simulations were done for each canopy type), to test the validity of the approach for partitioning the total gap fraction to between-crown and within-crown contributions. Generally, an error of about 0.05 exists in determining f_c and Φ by using an average crown radius and tree stem density rather than the actual model calculations of f_c . However, these errors are not of concern when estimating $\Omega_c(0)$ using the gap-fraction partitioning strategy discussed here.

Determining $\Omega_c(0)$ with f_c and Monte Carlo simulations

We used Monte Carlo simulations to derive a relationship between input values of Φ and f_c with $\Omega_c(0)$ computed by the model. By varying the model inputs of leaf area, crown diameter and stem density, we change the Φ and also adjust the portion of $f_{gap,t}(0)$ that comprises gaps occurring between individual tree crowns. Individual foliage elements (leaves or shoots) are randomly placed within each crown. Thus, when stem spacing in numerical simulations reaches a value where the perimeters of crowns significantly overlap each other, any amount of randomly placed foliage area within crowns will appear to be randomly distributed throughout the entire canopy. Although the forest appears to consist of one large crown of randomly dispersed foliage, in natural forest ecosystems additional clumping can occur within a crown as a result of branch architecture. Because of the complexity associated with clumping within crowns, it is accommodated separately. In the case of shoots, this is accomplished by using measured values of γ_e . Consequently, one potential source of bias exists in our model simulations. However, the majority of nonran-

Table 3. Comparison of fraction crown cover (f_c) and crown porosity (Φ) from Monte Carlo simulations (values represent the mean of 15 simulations for each canopy type) and estimates of the same quantities using the simplified approach to partition total gap fraction to within-crown and between-crown contributions. The simplified approach uses the mean plot stem density and tree crown radius to determine the quantity f_c , whereas the Monte Carlo value is the true value of f_c . Typical ranges of crown diameter reported in Table 2 were used in the simulations.

Quantity	Jack pine	Black spruce	Aspen
LAI	2.2	5.7	3.3
Stem density (stems ha ⁻¹)	1800	4460	847
Total gap fraction	0.58	0.40	0.41
Mean crown diameter (m)	1.94	1.38	3.4
f_c (Monte Carlo)	0.48	0.61	0.73
f_c (simple estimation)	0.53	0.67	0.77
Φ (Monte Carlo)	0.13	0.03	0.19
Φ (simple estimation)	0.09	0.09	0.23

dom gap sizes, which are removed from the zenith canopy gap-size distributions measured with the MVI (typically greater than 20–30 cm), occur between individual crowns. Therefore, the small bias arising from randomly distributing leaves or shoots in tree crowns probably does not greatly affect the accuracy of our general solution.

Values of Φ and f_c are used to determine a value of $\Omega_c(0)$ that is consistent with calculations resulting from numerical simulations of the canopy gap-size distribution. As the value of f_c approaches 1.15 (small amount of overlapping tree branches), Φ does not affect the value of $\Omega_c(0)$, so that the canopy has a random gap-size distribution at any zenith angle for all values of Φ . Subsequently, for any value of Φ , $\Omega_c(0)$ will not be less than 1.0 when $f_c \geq 1.15$. A nonlinear least-squares fit to approximately 250 Monte Carlo simulations (analyzing values of $\Omega_c(0)$) is performed for values of $f_c \geq 0.20$, and for all simulated values of Φ . A separate fit to the entire set of model data was performed for $0.04 \leq f_c \leq 0.30$ for two reasons. First, the error (RMS) associated with the curve fitting applied to the entire range of f_c (0.04–1.15) was higher; and second, the majority of forests studied will have values of f_c that are greater than 0.20. However, for sparse canopies where $f_c < 0.20$, a value of $\Omega_c(0)$ can still be determined. Ten equations are solved simultaneously to determine 10 coefficients ($a_0 \dots a_9$) that describe the following relationship between values of $\Omega_c(0)$, f_c , and Φ :

$$\Omega_c(\theta) = a_0 + a_1 f_c + a_2 \Phi + a_3 f_c \Phi + a_4 f_c^2 + a_5 \Phi^2 + a_6 \Phi^2 (f_c) + a_7 (f_c)^2 \Phi + a_8 f_c^3 + a_9 \Phi^3. \quad (3)$$

Values of each coefficient corresponding to the two curve-fitting exercises are given in Table 4. If the value of $\Omega_c(0)$ produced using Equation 3 is greater than 1.0, the value should be set equal to 1.0 (random distribution of foliage) and if $\Omega_c(0) < 0.0$, the value should be set to zero. Because Equation 3 produces values of $\Omega_c(0)$ with an $r^2 = 0.97$ compared with

numerically simulated model data, and has an RMS = 0.058 (Figure 7) for the fit to $f_c \geq 0.20$, a reasonable estimate of $\Omega_c(0)$ can still be acquired for most natural forest ecosystems without having any detailed information about canopy gap-size distribution. The RMS = 0.06 and $r^2 = 0.94$ for a fit using Equation 3 to the model data that includes f_c values between 0.04 and 0.30. Consequently, if a forest stand has a value of $f_c < 0.20$, an estimate can still be obtained using Equation 3 and the alternative set of coefficients reported in Table 2. Figure 8a is a plot of $\Omega_c(0)$ versus f_c for a range of values using the fit to modeled data for $f_c > 0.20$ and Figure 8b is for the fit of $\Omega_c(0)$ using values of f_c ranging from 0.04 to 0.30. We note that these two fits do not overlay one another precisely in the range of f_c between 0.20 and 0.30, but at $f_c = 0.25$, the difference is only ± 0.05 .

A comparison between measured values of $\Omega_c(0)$ obtained with the MVI in aspen, black spruce, and jack pine during BOREAS, and estimated values of $\Omega_c(0)$ is shown in Table 5. Two possible approaches can be used to calculate a value of $\Omega_c(0)$. The first method involves using mean values of Φ and f_c for a forest to obtain a characteristic mean value of $\Omega_c(0)$. With this method, the mean $\Omega_c(0)$ calculated with Equation 3

Table 4. Values for coefficients used in Equation 3 for forests with values of $f_c \geq 0.20$, or $f_c < 0.20$.

Coefficient	$f_c \geq 0.20$	$0.04 < f_c < 0.30$
a_0	-0.125	0.838
a_1	0.369	-8.138
a_2	-0.025	2.677
a_3	0.296	4.417
a_4	0.709	9.319
a_5	2.934	-3.358
a_6	-0.618	8.118
a_7	-0.688	-24.52
a_8	-0.109	19.565
a_9	-1.775	0.483

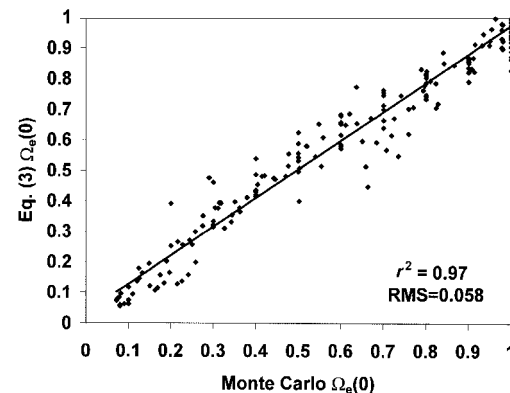


Figure 7. Monte Carlo simulations of $\Omega_c(0)$ for various values of crown porosity (Φ) and fraction of ground area covered by the horizontal projections of silhouette crown area ($f_c \geq 0.20$) plotted against values calculated with Equation 3 with the same values of Φ and f_c as inputs.

and data in Table 4 results in errors of 9, 22 and 1% in aspen, jack pine, and black spruce, respectively, compared with values of $\Omega_c(0)$ measured with the MVI. Alternatively, high and low extremes of $\Omega_c(0)$ could be averaged ($\Omega_{c,high}(0)$, $\Omega_{c,low}(0)$) using minimum and maximum values of Φ and f_c to obtain another value of $\Omega_c(0)$. With this approach, Equation 3 produces values of $\Omega_c(0)$ that have errors of 11, 11, and 8% in aspen, jack pine and black spruce, respectively, compared with MVI measurements. We conclude that either method will usually yield values of $\Omega_c(0)$ that are within about 15% of the actual value. As mentioned previously, the errors that were reported when estimating f_c and Φ (Table 3) by partitioning the total gap fraction into between-crown and within-crown components based on Monte Carlo modeling do not affect the estimation of $\Omega_c(0)$ enough to cause this simplified approach to appear constrained and limited in its applicability.

Determining a maximum value of $\Omega_c(\theta)$

To characterize the angular dependence of $\Omega_c(\theta)$, a minimum value of $\Omega_c(\theta)$ is determined at $\theta = 0$ and a value of $\Omega_c(\theta)$ is needed at $\theta = 90$. Because $\Omega_c(\theta)$ reaches its maximum value at $\theta = 90$, we refer to this value as the maximum possible element clumping index, $\Omega_{e,max}$. Generally, the maximum value of $\Omega_c(\theta)$ will be equal to 1.0, except in forests where trees are spaced such that when the canopy is viewed toward the horizon, the canopy gap-size distribution still resembles a clumped canopy, mainly because of large gap sizes that occur between individual crowns. This hypothesis is validated in Monte Carlo simulations with a low stem density (< 500 stems ha^{-1}) and small crown diameters (< 1 m). These values of stem density and crown diameters lead to values of $f_c < 0.20$. In these numerical simulations of sparse, pole-like forest stands, the canopy sunfleck size distribution has large, nonrandom gap sizes present at solar zenith angles from 0 to 85° , causing values of $\Omega_{e,max}$ to be less than 1.0. Based on Monte Carlo simulations of various types of stand architecture (in addition to black spruce, jack pine and aspen), we suggest that values of $\Omega_{e,max}$ for any forest stand can be obtained by an equation of the form:

Table 5. Stand architecture measurements and estimates for BOREAS NSA-OJP, SSA-OA and SSA-OBS study sites.

Value	SSA-OA	NSA-OJP	SSA-OBS
Crown diameter, D (m)	3.0	2.0	1.5
Stem density (trees ha^{-1})	800–1400	1200–2600	2850–4300
Stem spacing, λ (m): range	2.7–3.5	2.0–2.8	1.52–1.89
f_c : range	0.71–0.98	0.40–0.69	0.50–0.76
f_c : mean	0.84	0.55	0.63
$f_{gap,b}(0)$: range	0.02–0.29	0.31–0.60	0.24–0.50
$f_{gap,b}(0)$: mean	0.15	0.45	0.37
$f_{gap,t}(0)$	0.35	0.55	0.42
<i>MVI measurements</i>			
Porosity, Φ : range	0.23–0.34	0.01–0.40	0.01–0.24
Φ : mean	0.29	0.20	0.12
$\Omega_c(0)$ (MVI)	0.64	0.45	0.38
$\Omega_c(0)^1$	0.70	0.35	0.38
$\Omega_{c,low}(0)^2$	0.57	0.13	0.22
$\Omega_{c,high}(0)^2$	0.85	0.66	0.59
$\Omega_{e,mean}(0)^3$	0.71	0.40	0.41
$\Omega_{e,max}$	1.0	1.0	1.0
p^4	3.0	1.72	1.72
k^4	1.6	2.38	2.38
χ	1.75	3.5	5.0

¹ Value estimated using Equation 3 and mean values of f_c and γ .

² Values estimated using Equation 3 and maximum and minimum values of f_c and γ .

³ Mean of high and low values computed using Equation 3.

⁴ Values represent coefficients used in Equation 5 to represent best-fit to data in Figure 5.

$$\Omega_{e,max} = \left(\frac{ND}{\sqrt{A}} \right)^{0.7}, \quad (4)$$

where N is number of stems within ground area A , and D is crown diameter. If the quantity $ND/(A^{1/2})$ in Equation 4 > 1.0 , then the value of $\Omega_{e,max} = 1.0$. Values of $\Omega_{e,max}$ are plotted in Figure 9 for a range of $ND/(A^{1/2})$ from 0 to 1.0 using Equation 4.

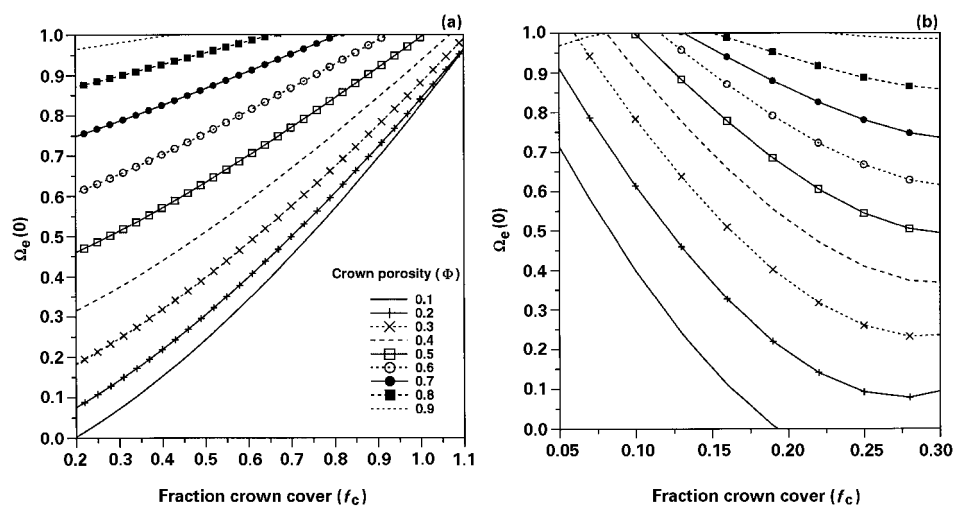


Figure 8. (a) Relationship between crown porosity (Φ), fractional crown cover (f_c) and zenith clumping index ($\Omega_c(0)$) for values of $f_c \geq 0.20$ calculated with Equation 3. (b) The same relationship as in (a) except that values of f_c were between 0.04 and 0.30 based on the appropriate set of coefficients from Table 4 in Equation 3.

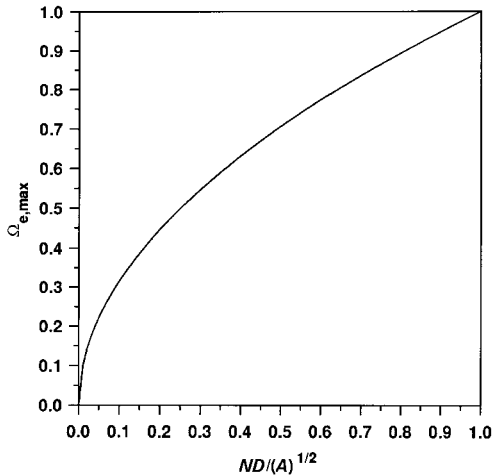


Figure 9. Estimates of maximum possible element clumping index ($\Omega_{e,\max}$) plotted against the ratio $ND/(A)^{1/2}$ where N = number of trees per unit area A , and D = typical crown diameter.

Characterizing the relationship of $\Omega_e(\theta)$ with changing zenith angle

The final step to our approach for characterizing direct beam penetration within a nonrandom forest by Equation 2 specifies the angular dependence of $\Omega_e(\theta)$ with a simple equation. Kucharik et al. (1997) show that, for an aspen forest, $\Omega_e(\theta)$ can be characterized by using TRAC measurements of $\Omega_e(\theta)$ made at a limited number of angles, or MVI measurements of $\Omega_e(0)$ if the proper angle adjustments are made with the following equation:

$$\Omega_e(\theta) = \frac{\Omega_{e,\max}}{[1 + b \exp(-k(\theta)^p)]}, \quad (5)$$

where p and k are constants, θ is zenith angle expressed in radians, and b is solved from a rearrangement of Equation 5 using a known value of $\Omega_e(\theta)$ (e.g., $\theta = 0$). The rearranged Equation 5 used to solve for b is given by:

$$b = \frac{\Omega_{e,\max} - \Omega_e(\theta)}{\Omega_e(\theta) \exp(-k(\theta)^p)}. \quad (6)$$

Values of $\Omega_e(0)$ and $\Omega_{e,\max}$ are known. The only unknowns are the values of p and k , which control the response of $\Omega_e(\theta)$ with zenith angle. For aspen, values of $p = 3.0$ and $k = 1.6$ produce the "best-fit" to model simulations (Kucharik et al. 1997). In jack pine and black spruce stands, which have distinctively different crown architecture from aspen, $p = 1.72$ and $k = 2.38$ (Table 5). Monte Carlo simulations have shown that the change in $\Omega_e(\theta)$ from 0 to 50° is more pronounced for boreal conifers than for aspen. The data in Figure 5 are the best-fit approximations of $\Omega_e(\theta)$ in aspen, oak, sugar maple, black spruce and jack pine based on MVI, TRAC, and model results. After examination of Monte Carlo simulations, we conclude that crown depth and crown diameter control the change in $\Omega_e(\theta)$ with increasing zenith angle. Therefore, we

define a value, χ , that describes the ratio of crown depth to crown diameter, to adjust for the angular dependence of $\Omega_e(\theta)$.

Based on the results of two independent tests that determined which factor (p or k) has the largest control over the change in $\Omega_e(\theta)$ with angle in Equation 5 and how it could be formulated to work in a variety of canopies (in addition to boreal forests) based on a constant value for k , we suggest that a k value of 2.2 can be used in Equation 5 and the quantity p can be a variable based on values of χ . This simplifying approach, which requires that only one additional variable needs to be adjusted in Equation 5, does not sacrifice the applicability of Equation 5 to almost any type of forest canopy architecture. We note that the chosen value for k is not a linear mean of the values that best approximate the modeled canopies (i.e., 1.6 for aspen and 2.38 for conifers). We determined the value of k that produced the lowest RMS difference between $\Omega_e(\theta)$ values produced with Equation 5 using: (1) the k value that best-fit the model results in each simulation and (2) a constant k value that could be applied accurately for all canopy types simulated. A quantitative comparison of results produced using Equation 5 with the best-fit curves (some of which are plotted in Figure 5) suggests that a value of p can be approximated by an equation of the form:

$$p = -0.461\chi + 3.8. \quad (7)$$

Generally, if χ is ≤ 1.0 , $p = 3.34$; this is a solution for crowns with a spherical shape that may be applied to many full-cover deciduous canopies (e.g., oak, sugar maple). If χ is ≥ 6.1 (values typical of tall, thin coniferous trees), values of p are set to a value of 1.0. If a value of χ for a species is less than 1.0 or greater than 6.1, some degree of uncertainty may exist as to whether the value of p used in Equations 5 and 6 is the most accurate for the species. However, we argue that the range of values reported represents values typical to many forest species. Table 6 shows typical values of χ , $\Omega_e(0)$ and LAI for aspen, black spruce and jack pine, estimated from data collected at the BOREAS study sites and for oak and sugar maple. Results of Equation 5 for the five species measured by the MVI are plotted in Figure 10 along with the "best-fit" results plotted in Figure 5 for comparison. The RMS difference between the best-fit and modeled values of $\Omega_e(\theta)$ based on estimates of p from Equation 7 and $k = 2.2$ is typically less than 0.05 for all five forest types, providing support for the conclusion that our general solution can give reasonable estimates for a wide range of forest canopy architecture types.

Conclusion

Three boreal forest species, black spruce, jack pine and aspen, were found to exhibit a clumped stature. The degree of clumping was dependent on the view or sun zenith angle, which is related directly to the canopy gap-size distribution. Results of MVI measurements and Monte Carlo simulations show that the zenith element clumping index ($\Omega_e(0)$) is typically around 0.4–0.5 in boreal conifers (jack pine and black spruce) and $\Omega_e(0) = 0.65$ in aspen. Total LAI estimated from MVI measurements of the canopy gap fraction, branch architecture, and

gap-size distribution show that LAI = 3 in jack pine, 3.3 in aspen, and about 6 in black spruce. These canopies appear to have a high degree of foliage organization when viewed toward the zenith, and appear to have random distributions of foliage elements (shoots or leaves) when the canopy is viewed at high zenith angles. Two full-cover temperate deciduous species, oak and sugar maple, exhibited nearly random spatial distributions of foliage at any view angle. Values of $\Omega_c(0)$ in these forests were typically near 0.90, with LAI = 4 in oak, and 6 in sugar maple. These observations, along with the results of Monte Carlo simulations of many canopy architecture types, confirmed that an element clumping index incorporated into the Beer-Lambert law can characterize the radiation regime in nonrandom forest canopies when random assumptions would be invalid. Consequently, the element clumping index is an important parameter that can be used to adjust indirect estimates of LAI derived from gap fractions measurements that would normally underestimate the true LAI because of foliage clumping. Detailed measurements of the canopy gap-size distributions are not necessary to obtain approximate estimates of the clumping index with zenith angle.

Because distinct relationships exist between stand structure and foliage spatial patterns, the canopy gap-size distribution can be used to describe radiation penetration in forests as a function of angle. However, it is technically difficult to obtain multi-angular measurements of gap-size distributions. We have connected canopy structural values that are relatively easy to measure (i.e., crown depth, stem spacing, crown diameter, and the zenith gap fraction partitioned into between-crown and within-crown components) to a series of empirical relationships to estimate $\Omega_c(\theta)$. Although this theory may be an oversimplification, we believe that the approach is robust and applicable to most types of canopy architecture. Application of this theory to BOREAS sites, which represent some of the most clumped forest species in the world, yielded encouraging results when compared with MVI measurements.

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Table 6. Zenith clumping factors $\Omega_c(0)$ for various species measured with the MVI, values of the crown depth to diameter ratio (χ), and estimates of semi-surface leaf area index (LAI).

Species (Location)	χ	$\Omega_c(0)$	LAI
Sugar maple (Wisconsin, USA)	~1	0.95	6
Oak (North Carolina, USA)	~1	0.90	4.5
Aspen (Saskatchewan/Manitoba, Canada)	1.5–2.0	0.65	3.0
Jack pine (Manitoba, Canada)	3–4	0.45	2.5
Black spruce (Saskatchewan, Canada)	5–6	0.40	5.5

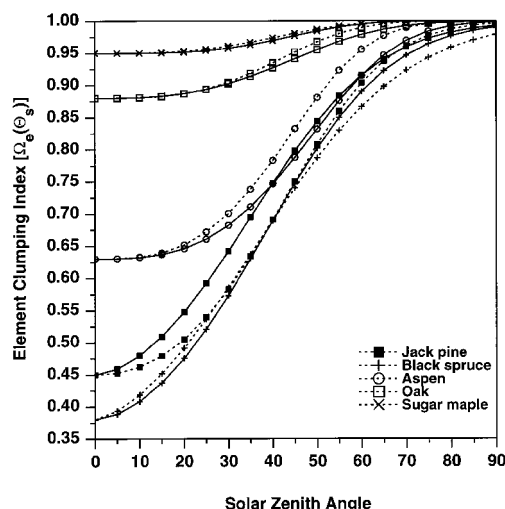


Figure 10. Results of general solution of $\Omega_c(\theta)$ calculated by Equation 5 with independent values of χ and p for the five forest species plotted in Figure 5. Dashed lines represent the result of Equation 5 with $k = 2.2$ and $p = 3.0$ for SSA-OA, $p = 3.34$ for sugar maple and oak, $p = 2.19$ for NSA-OJP, and $p = 1.50$ for SSA-OBS. Solid lines represent the best fit to data for each forest as plotted in Figure 5.

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Appendix

Notation

A	Ground area (m^2)
D	Typical crown diameter (m)
f_c	Fractional area coverage of crowns; m^2 crown silhouette area per m^2 ground area obtained with projection of a crown from nadir
$f_{gap,b}(0)$	Canopy gap fraction contribution from between-crown gaps estimated with a zenith view angle
$f_{gap,c}(0)$	Canopy gap fraction contribution from within-crown gaps estimated with a zenith view angle
$f_{gap,t}(0)$	Transmission of direct beam radiation through canopy due to all foliage elements (leaves, shoots, branches, stems) estimated with a zenith view angle; $f_{gap,t}(0) = f_{gap,b}(0) + f_{gap,c}(0)$
k	Parameter used to determine values of $\Omega_e(\theta)$
$K(\theta)$	Canopy extinction coefficient; mean projection of a unit area of foliage in the direction of light beam or view direction (θ)
L	Total hemi-surface area index of non-woody foliage per unit ground surface area derived from adjustments to gap fraction measurements
$L_{e,leaf}$	Portion of $L_e(\theta)$ measured with the MVI that is just leaves
$L_{scale,MVI}$	Total hemi-surface area index of non-woody foliage per unit ground area derived from MVI measurements of

	the canopy gap fraction adjusted for foliage clumping and light intercepting branch area
L_t	Total hemi-surface area of all foliage per unit ground surface area in canopy
L_{tot}	Total non-woody foliage hemi-surface area in a canopy derived from allometric equations; one-half the total surface area of non-woody foliage elements per unit ground surface area
$L_e(\theta)$	Indirect measure of hemi-surface area index of all foliage (leaves, shoots, branches, stems) in a canopy based on canopy gap fraction inversion technique; one-half the total surface area of all foliage per unit ground surface area; referred to as the “effective LAI”
N	Number of tree stems per unit ground area (A)
$P(\theta)$	Probability of direct beam transmission through a plant canopy at zenith angle assuming azimuthal symmetry of the leaf angle distribution
p	Parameter used in Equation 5 based on crown depth to crown diameter ratio (χ)
γ_e	Within-shoot clumping factor accounting for the clumping of needles on shoots; defined as 1/2 total needle surface area to 1/2 total shoot envelope surface area (Chen et al. 1997)
λ	Mean tree stem spacing (μ)
Φ	Crown porosity ($f_{gap,c}(0)/f_c$)
$\Omega(\theta)$	Total nonrandomness correction factor including needles clumped on individual conifer shoots and the clumping of branches and shoots on tree crowns ($\Omega(\theta) = \Omega_e(\theta)/\gamma_e$)
$\Omega_{e,max}$	Maximum possible value of $\Omega_e(\theta)$
$\Omega_e(\theta)$	Nonrandomness correction factor for spatial distribution of primary foliage elements (leaves on broadleaf trees or shoots on conifers) in tree crowns at any angle θ
$\Omega_e(0)$	Element clumping index for leaves or shoots estimated using MVI measurements of the canopy gap-size distribution looking toward the canopy zenith
$\Omega_{e,high}(0)$	Highest estimate of zenith element clumping index for a forest using maximum observed crown density and largest value of crown porosity
$\Omega_{e,low}(0)$	Lowest estimate of zenith element clumping index for a forest using minimum observed crown density and smallest value of crown porosity
ϕ	Azimuth angle
θ	Zenith angle
χ	Ratio of crown depth to crown diameter

Abbreviations

BLC	Base of live crown
LAI	Leaf area index; hemi-surface area of leaves (one-half the total surface area) per unit ground surface area
LAI-2000	Instrument developed by Li-Cor, Inc. (Welles 1990) that indirectly measures LAI of canopies by measuring canopy gap fraction at 5 different angles
MVI	Multiband Vegetation Imager (Kucharik et al. 1997, 1998)
PAR	Photosynthetically active radiation (400–700 nm)
PCA	Plant canopy analyzer (LAI-2000)
TRAC	Instrument developed by Chen and Cihlar (1995) that estimates canopy gap fraction and nonrandomness as a function of solar zenith angle (Tracing Radiation and Architecture of Canopies)