

Plant canopy gap-size analysis theory for improving optical measurements of leaf-area index

Jing M. Chen and Josef Cihlar

Optical instruments currently available for measuring the leaf-area index (LAI) of a plant canopy all utilize only the canopy gap-fraction information. These instruments include the Li-Cor LAI-2000 Plant Canopy Analyzer, Decagon, and Demon. The advantages of utilizing both the canopy gap-fraction and gap-size information are shown. For the purpose of measuring the canopy gap size, a prototype sunfleck-LAI instrument named Tracing Radiation and Architecture of Canopies (TRAC), has been developed and tested in two pure conifer plantations, red pine (*Pinus resinosa* Ait.) and jack pine (*Pinus banksiana* Lamb). A new gap-size-analysis theory is presented to quantify the effect of canopy architecture on optical measurements of LAI based on the gap-fraction principle. The theory is an improvement on that of Lang and Xiang [Agric. For. Meteorol. **37**, 229 (1986)]. In principle, this theory can be used for any heterogeneous canopies.

Key words: Leaf-area index, canopy gap size, canopy architecture, sunflecks, vegetation index, TRAC.

1. Introduction

In studies of the Earth's ecosystems and their interaction with climate, it is frequently necessary to know the leaf-area index (LAI) of vegetation cover. LAI, defined as one half the total leaf area per unit ground surface area,¹ determines the productivity of the surface and hence affects physical and biophysical interactions between the surface and the atmosphere.

For large areas, reflected spectral radiances that are remotely sensed from airborne and spaceborne platforms have been used to derive LAI. Uncertainties in LAI calculated with vegetation indices composed of the reflected radiances, such as the normalized difference vegetation index and the simple ratio, are often very large, especially for forested surfaces.^{2,3} The uncertainties arise from several sources, including foliage architecture (which affects radiation interception by the foliage and the angular distribution of the reflected radiances), the effects of the understory and soil background, and to a considerable extent the quality of ground truth LAI data⁴ obtained from both direct and indirect methods. Since direct measurements of LAI of forests are time consuming and

destructive in nature, indirect methods are often used. These methods include optical instruments and allometric relationships. Allometric relationships such as that between LAI and sapwood area or tree trunk diameter are often stand specific; i.e., they depend on species, season, age, stand density, tree crown size, and other stand attributes.^{5,6} Optical instruments are therefore very attractive to many investigators because of the speed and nondestructive nature of the measurements.

Optical instruments measure the amounts of direct or diffuse light penetrating the canopy from which the LAI is derived. For example, the Plant Canopy Analyzer (PCA) (LAI-2000, Li-Cor, Inc., Lincoln, Nebraska, see Welles⁷) detects the penetrating diffuse light at five angles simultaneously, and hence avoids the need for knowing the foliage-angle distribution. The Demon (Centre for Environmental Mechanics, Canberra, Australia; see Lang and Xiang⁸) and the Sunfleck Ceptometer (Decagon Device, Pullman, Washington) make use of the transmitted direct light. A minimum of half a clear day is required to obtain multiangular measurements in determining LAI for canopies with an unknown foliage-angle distribution. The percentage of direct or diffuse light transmitted through the canopy at a given angle is proportional to the canopy gap fraction at that angle. Hence these optical instruments essentially measure the canopy gap fraction, which is the percentage of sky seen from underneath the canopy. To invert from gap fraction to LAI, an assumption must be made on the spatial

The authors are with the Applications Division, Canada Centre for Remote Sensing, 419-588 Booth Street, Ottawa, Canada K1A 0Y7.

Received 9 August 1994; revised manuscript received 19 April 1995.

0003-6935/95/276211-12\$06.00/0.

© 1995 Optical Society of America.

distribution of the foliage elements. One obvious problem in using these instruments in conifer stands is that needles are grouped together in shoots and the amount of needle area in a shoot cannot be detected, especially when the shoot is too dense to allow much light penetration. Gower and Norman⁹ proposed a simple correction to the PCA measurements of LAI that uses the ratio of leaf area in a shoot to the shoot silhouette area. The underlying assumptions for this simple correction are that shoots are (a) the basic foliage units (elements) responsible for light interception and (b) randomly distributed in the canopy. However, in conifer canopies, the spatial positions of shoots are confined within tree crowns and branches and are not random. Chen and Black¹⁰ found that such nonrandomness of shoot positions reduces indirect measurements of LAI by approximately 35% for a Douglas fir canopy. In their case, the indirect measurement of LAI with the PCA was only 31% of a direct measurement through destructive sampling. Clumping of needles within shoots accounts for the rest, i.e., $(100 - 31 - 35)\% = 34\%$, of the difference between the indirect and the direct measurements.

Because LAI measurements based on the gap-fraction principle inevitably suffer from errors due to nonrandom foliage spatial distributions, attempts to utilize the canopy gap-size information have been made. Gap size refers to the physical dimensions of gaps. It differs from the gap fraction because for the same gap fraction, there can be different gap-size distributions. Using hemispherical photographs of a deciduous canopy, Neumann *et al.*¹¹ derived a correction for LAI from a conditional probability of rays, separated by a distance Δd , passing through the same gap in the canopy. In this approach, the conditional probability increases with the size of the gap but is very sensitive to the choice of Δd . They found it difficult to provide justification for the particular values used. In another study, Chen and Black¹⁰ quantified the effect of foliage clumping at scales larger than the shoots (elements) with an element-clumping index. Using measurements of the transmitted light at 12-cm spacing along a tram transect near the forest floor in a Douglas fir stand, they obtained canopy gap-size distributions from which an element-clumping index was derived. From a gap-size distribution, they also derived several canopy architectural parameters that are of interest for modeling radiation regimes in plant canopies. An important assumption used in their analysis is the random spatial distribution of clumps (tree crowns). This assumption may be good for open natural forest stands, where the spatial distribution of tree crowns is close to random. However, in plantations, where trees are regularly or artificially spaced, the assumption is violated, and the usefulness of their gap-size-analysis method becomes limited.

In the present paper, a new theory is developed to derive the element-clumping index from a canopy gap-size distribution. This theory eliminates the need for assumptions of spatial-distribution patterns

of foliage elements and clumps and can be applied to all types of plant canopies. A prototype sunfleck-LAI instrument named Tracing Radiation and Architecture of Canopies (TRAC) has been developed at the Canada Centre for Remote Sensing by the senior author for measurement of sunflecks along straight transects beneath the canopy to obtain the canopy gap-size information from which to calculate LAI and canopy architectural parameters. The instrument has been tested in two conifer plantations.

2. Theory

Sunflecks on the ground result from gaps in the overlying canopy in the Sun's direction. From the sunflecks, a distribution of the canopy gap size can therefore be obtained after considering the penumbra effect (Appendix B). If a canopy is homogeneous at large scales, sunfleck measurements on a transect in any direction that are more than 10 times longer than the average tree spacing can statistically represent the canopy with an accuracy of 95% according to Poisson probability theory. Otherwise, sunfleck measurements represent only part of the canopy measured. Naturally, gaps along the transect vary irregularly in size. For the data analysis, the measured gaps are rearranged in an ascending or descending order by their size, and a gap-size accumulation function $F(\lambda)$ can thus be formed (Fig. 1), in which $F(\lambda)$ denotes the fraction of the transect occupied by gaps (sunflecks) larger than λ . In Fig. 1, $F(\lambda) = 0$ for λ values larger than λ_1 since no gaps are found to be larger than λ_1 . If λ_1 is the only gap on the transect of length L_t , $F(\lambda)$ in Fig. 1 would appear to be a horizontal line from 0 to λ_1 at a value of λ_1/L_t . Since many smaller gaps exist, $F(\lambda)$ increases as λ decreases. At $\lambda = 0$, $F(\lambda)$ becomes the fraction of the transect occupied by all gaps, i.e., the total gap fraction of the canopy.

A. Random Canopy

Miller and Norman¹² show that for a canopy with horizontal leaves randomly distributed in space and

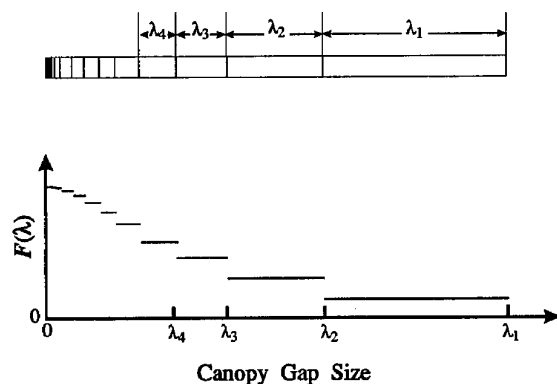


Fig. 1. Schematic canopy gap-size distribution measured on a transect beneath the canopy, where $F(\lambda)$ is the fraction of the transect that is occupied by gaps larger than λ . Gaps λ_i are sorted in a descending order from left to right (top), and $F(\lambda)$ is formed as the accumulated gap fraction starting from the largest gap λ_1 .

the Sun at zenith, $F(\lambda)$ is determined as follows:

$$F(\lambda) = (1 + \rho w \lambda) \exp[-\rho(\sigma + w \lambda)], \quad (1)$$

where ρ is the number of leaves per unit ground surface area, σ is the area of a leaf, and w is the average width of leaves in the direction perpendicular to the transect. Following the methodology used by Chen and Black,¹⁰ we can rewrite Eq. (1) as

$$F(\lambda) = \left(1 + L \frac{\lambda}{W}\right) \exp\left[-L\left(1 + \frac{\lambda}{W}\right)\right], \quad (2)$$

where $L = \rho\sigma$, i.e., the LAI, and W is the characteristic width of a leaf, defined as

$$W = \sigma/w. \quad (3)$$

Since σ is proportional to w^2 , W is proportional to w ; i.e.,

$$W = cw, \quad (4)$$

where c is a constant depending on the shape of the leaves. For circular disks, w is the diameter and $c = \pi/4$.¹⁰

For conifer stands, shoots are identified as the basic foliage units or elements (see Section 4). To apply Eq. (2) to plant canopies with the Sun at a nonzero zenith angle and nonhorizontal foliage elements, several modifications need to be made. First, L is to be replaced by L_p (projected L_E), defined as

$$L_p = \frac{G(\theta)L_E}{\cos \theta}, \quad (5)$$

where $G(\theta)$ is the projection coefficient determined by the incident angle θ and the distribution of the foliage element normal,¹³ being 0.5 for a random (spherical) distribution of the normal. The term $1/\cos \theta$ compensates for the path length of a beam passing through the canopy at a given angle θ , and L_E is the element-area index. Here the distinction between L and L_E is made. If leaves are treated as the elements, L_E is the LAI (L), but if shoots are identified as elements, L_E becomes the shoot-area index (the definition of shoot area is given in Section 3).

The second modification to Eq. (2) is to replace W with W_p . W_p is the mean width of the shadow of a foliage element projected on a horizontal surface and is defined as

$$W_p = \frac{\overline{W}}{\cos \theta_p}, \quad (6)$$

where \overline{W} is the mean width of an element projected on a plane perpendicular to the direction of the solar beam. The term $1/\cos \theta_p$ in Eq. (6) takes into account the elongation of the element shadow on a horizontal plane in the direction of the measuring transect. θ_p , which may be termed the width projection angle, depends on the shape of the element and the azimuthal angles of the Sun and the transect.

For spheres, it is calculated as (Appendix C):

$$\cos \theta_p = \left(\frac{\cos^2 \theta + \tan^2 \Delta\beta}{1 + \tan^2 \Delta\beta}\right)^{1/2}, \quad (7)$$

where $\Delta\beta$ is the difference in the azimuthal angles of the Sun and the transect. In Eq. (7), θ_p varies from 0 at $\Delta\beta = \pi/2$ to θ at $\Delta\beta = 0$ or π . After these modifications, Eq. (2) becomes

$$F(\lambda) = \left(1 + L_p \frac{\lambda}{W_p}\right) \exp\left[-L_p\left(1 + \frac{\lambda}{W_p}\right)\right]. \quad (8)$$

B. Nonrandom Canopies

The spatial distribution of foliage elements (e.g., shoots) is seldom random, and therefore any distribution [denoted $F_m(\lambda)$] measured in a plant canopy is very unlikely to overlap with $F(\lambda)$ for canopies with random foliage distributions. Foliage in plantations and natural forest stands is generally clumped, resulting in larger canopy gap fractions than those of random canopies with the same LAI. When a canopy is clumped, not only does the gap fraction increase, but also the gap-size distribution changes. This change can be shown as the difference between $F(\lambda)$ and $F_m(\lambda)$. Therefore the difference provides information on the foliage spatial distribution in a canopy. A new method is developed in this study to derive the element-clumping index from a measured gap-size distribution. The clumping index Ω_E is given in the following equation:

$$P(\theta) = \exp[-G(\theta)\Omega_E L_E / \cos \theta], \quad (9)$$

where $P(\theta)$ is the probability of a solar beam at an incidence angle θ penetrating the canopy without being intercepted. Equation (9) demonstrates that canopy gap-fraction measurements by the use of the PCA or other optical instruments only provide information for the calculation of $\Omega_E L_E$ rather than L if Ω_E is unknown. By definition, $P(\theta)$ equals the canopy gap fraction in the same direction; i.e., $P(\theta) = F_m(0)$ at θ . Therefore

$$\Omega_E L_E = -\frac{\cos \theta}{G(\theta)} \ln[F_m(0)]. \quad (10)$$

If we know an equivalent $F(\lambda)$ for a canopy, i.e., the gap-size distribution at which the foliage elements are randomly spaced ($\Omega_E = 1.0$), we have

$$L_E = \frac{\cos \theta}{G(\theta)} \ln[F(0)], \quad (11)$$

where $F(0)$ is $F(\lambda)$ at $\lambda = 0$. Combining Eqs. (10) and (11) results in

$$\Omega_E = \frac{\ln[F_m(0)]}{\ln[F(0)]}. \quad (12)$$

Equation (12) states that the clumping index can be calculated from the measured gap fraction $F_m(0)$ and

an imaginary gap fraction $F(0)$ for a canopy with a random spatial distribution of the foliage elements. It is demonstrated here that the random canopy gap fraction $F(0)$ can be derived from a measured gap-size distribution $F_m(\lambda)$.

To find $F(0)$, it is necessary to know $F(\lambda)$ [Eq. (8)], which requires input of the element size W_p and the projected element-area index L_p defined in Eq. (5). For broad-leaf canopies, W_p can be taken as the average leaf width, but for needle-leaf canopies, it is questionable to treat needles as the foliage elements. Gower and Norman⁹ and Fassnacht *et al.*¹⁴ made corrections to the PCA measurements based on the assumption that shoots of conifers are the basic foliage units responsible for radiation interception. This approach was also used by Deblonde *et al.*¹⁵ From sunfleck-size distributions in a Douglas fir stand, Chen and Black¹⁰ derived an element size that is slightly larger than the characteristic size of the shoots. These findings are consistent with visual observations that needles are closely grouped in shoots that appear to be distinct units of foliage. In the present study, Chen and Black's approach is used to determine the element size, which agrees with these previous findings.

To determine L_p , it is required to know L_E [Eq. (5)], but L_E is also unknown. However, a measured gap-size distribution $F_m(\lambda)$ helps solve the problem. When a canopy is clumped (such as conifer stands, where the spatial positions of shoots are confined within individual branches and tree crowns), large canopy gaps appear; i.e., the gaps between tree crowns and branches are generally larger than those within these structures. In other words, large gaps are more frequently observed in clumped canopies than in random canopies. These large gaps increase the canopy gap fraction and therefore affect the indirect measurements of LAI. If we know the probability of the appearance of large gaps for a random canopy, i.e., $F(\lambda)$, given the values of W_p and L_p , we can remove the effect of these large gaps on LAI measurements by removing them from the total gap fraction. As the value of L_p is unknown, we first use $\Omega_E L_E$ as L_E ; i.e., L_p is first taken as $-\ln[F_m(0)]$ from Eqs. (5) and (10) to produce the first estimate of $F(\lambda)$. Gaps appearing at probabilities in excess of $F(\lambda)$ are then removed or truncated. After the first round of gap removal, a new gap-size distribution $F_{mr}(\lambda)$ is computed. In the second step, L_p is assigned the value of $-\ln[F_{mr}(0)]$, which is larger than its first estimate because $F_{mr}(0)$ is smaller than $F_m(0)$. The final value of L_p is found after several iterations of the same steps until no increase in L_p is found, i.e., until the new distribution $F_{mr}(\lambda)$ closely overlaps $F(\lambda)$.

Figure 2 demonstrates the changes in $F_{mr}(\lambda)$ with the iterations. Curve a1 is the measured distribution $F_m(\lambda)$, and curve b1 is the predicted distribution $F(\lambda)$ for the case of random foliage distribution determined by the use of measured W_p and the first estimate of L_p . The nonrandomness of the canopy can be seen from the difference in curves a1 and b1:

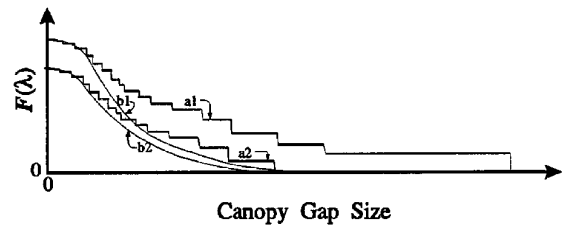


Fig. 2. Gap-size distribution and redistribution after a gap-removal process, where a1 is a measured gap-size distribution $F_m(\lambda)$, b1 is the first estimate of $F(\lambda)$ for a random canopy, a2 is the redistribution $[F_{mr}(\lambda)]$ after two large gaps are removed, and b2 is the second estimate of $F(\lambda)$. In finding the final $F_{mr}(\lambda)$ for the calculation in Eq. (16), the removal of gaps appearing at probabilities in excess of $F(\lambda)$ is repeated until $F_{mr}(\lambda)$ is brought to the closest agreement with $F(\lambda)$.

many large gaps appear at probabilities much larger than $F(\lambda)$. After some of the excessive gaps are removed, the first estimate of $F_{mr}(\lambda)$ is formed as curve a2, and the second $F(\lambda)$, curve b2, is obtained with the same W_p but different L_p obtained from $F_{mr}(\lambda)$, ensuring that $F(0) = F_{mr}(0)$. In the operation, when a gap of size λ_i is removed, $F_{mr}(\lambda)$ at all λ values smaller than λ_i is reduced by λ_i/L_p . This makes the curve $F_m(\lambda)$ shift downward by the same amount. Curves a2 and b2 still exhibit large differences, and further removal of the remaining large gaps is still needed. Since in the random case there is always a nonzero probability for the appearance of a gap of however large a size, a small portion of a truncated gap remains. Many such partial truncations make $F_{mr}(\lambda)$ smoother after each iteration. The iteration stops when either the increase in L_p becomes very small (less than 0.01) or a portion of $F_{mr}(\lambda)$ falls below $F(\lambda)$. The latter case happens more often because measured distributions at small λ values always deviate to some extent from the ideal random conditions.

Figure 3 illustrates the rationale for the gap-removal approach. When it is assumed that an originally random canopy is split into many sections with gaps inserted between them, these foreign gaps increase the gap fraction and make the apparent foliage area available for radiation interception smaller. The gap-removal process discussed above can therefore be regarded as a reversal of the gap-insertion process, which restores the random state of

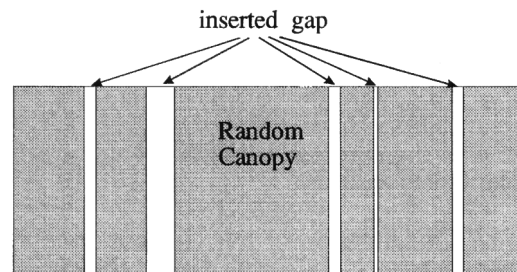


Fig. 3. Imaginary plant canopy with gaps inserted in a random canopy. These inserted gaps mixing with gaps in the original canopy can be found through gap-size analysis.

the canopy. Since in a random canopy the gap-size distribution follows a predictable pattern, these foreign gaps can be identified in a measured gap-size distribution. In reality, the separated pieces with local randomness do not exist, and gaps resulting from foliage clumping are mixed with gaps that exist in random canopies. Therefore the insertion of gaps depicted in Fig. 3 is not a realistic case. However, the gap-size-analysis method presented above does not require the assumption of local randomness because only the gaps resulting from foliage clumping are removed, and the gaps appearing at probabilities in accord with $F(\lambda)$ are kept. In other words, in the gap-removal process, the foliage elements are computationally rearranged in space to form a random canopy.

After the removal or truncation of large gaps the canopy becomes compacted; i.e., the ground surface area it occupies is reduced by the total fraction of gaps (Δg) removed,

$$\Delta g = F_m(0) - F_{mr}(0). \quad (13)$$

By definition, the element-area index for the compacted canopy is

$$L_{Ec} = -\frac{\cos \theta}{G(\theta)} \ln[F_{mr}(0)]. \quad (14)$$

If the elements are redistributed in the original total area, i.e., the compacted canopy area is expanded by Δg , the element-area index after the expansion is

$$L_E = -\frac{\cos \theta}{(1 + \Delta g)G(\theta)} \ln[F_{mr}(0)]. \quad (15)$$

From Eqs. (10) and (15), it can be shown that

$$\Omega_E = \frac{(1 + \Delta g) \ln[F_m(0)]}{\ln[F_{mr}(0)]}. \quad (16)$$

Since $F_{mr}(0) = F(0)$, this is a slight modification to Eq. (12), in which canopy compaction as a result of the gap removal was not considered for convenience of derivation. The total gap fraction $F_m(0)$ can be accurately measured as the transmittance of direct light through the canopy. The accuracy in the calculated Ω_E values lies largely in determining $F_{mr}(0)$ from a measured gap-size distribution. It is shown below that F_{mr} can also be accurately determined.

Equation (16) shows that Ω_E can be obtained through gap-size analysis without specific knowledge of $G(\theta)$. To obtain L_E , it is necessary to know $G(\theta)$ [Eq. (15)] or to obtain multiangular measurements from which to derive $G(\theta)$.

When shoots of conifer trees are identified as elements, Ω_E accounts for the effect of foliage clumping at scales larger than the average size of the shoots, and an additional parameter γ_E is needed to include the effect of foliage clumping within shoots. γ_E is defined as the ratio of half the total leaf area in a shoot to half the total shoot area (defined in Section

3). The total foliage clumping index Ω including the effect of nonrandomness at all scales is then given as¹⁰

$$\Omega = \Omega_E / \gamma_E. \quad (17)$$

From Eq. (9), (17), and the following equation,^{10,16}

$$P(\theta) = \exp[-G(\theta)\Omega L / \cos \theta], \quad (18)$$

it can be derived that

$$\gamma_E = L / L_E, \quad (19)$$

where L is the LAI. In this definition, it is assumed that the contribution of the supporting woody material is negligible. However, $P(\theta)$ measured from optical instruments contains the effect of this material, and therefore L is more accurately considered to be the plant-area index, including all material above the ground. When L is considered as a plant-area index, a small error in the calculation of L is expected to occur when Eq. (19) is used, since it is derived for shoots only. An adjustment of γ_E to account for the influence of woody material may be necessary when the woody component is considerable, but no such adjustment is made in this study. Equation (19) states that optical methods are sensitive only to the shoot area but not to the needle area in a shoot. To obtain the leaf- (needle-) area index, the remaining task is to measure the average needle area per unit shoot area through destructive sampling.

The product of Ω and L is referred to as the effective LAI (L_e)¹⁷; i.e.,

$$L_e = \Omega L. \quad (20)$$

L_e is the quantity directly measured by the PCA and other optical instruments. In the present study, we calculate L with Eq. (20), in which L_e is directly obtained from the PCA and Ω is determined from gap-size analysis by the use of the TRAC data and measurements of needle-shoot-area ratio.

It is emphasized that L derived in this way [Eq. (20)] includes half the surface area of all material above the ground (the leaves and the supporting woody material) because the measurements of L_e with the PCA and the measurements of Ω_E with the TRAC contain the effect of nonfoliage areas. In stands where the contributions of nonfoliage areas are considerable, the actual LAI may be significantly smaller than L obtained from Eq. (20). In the present study, L is therefore referred to as the plant-area index.

3. Experimental Methods

Measurements of LAI were made in two conifer plantations near the Petawawa National Forestry Institute (46° 00' N and 77° 27' W) in Ontario, Canada. One plantation is red pine (*Pinus resinosa* Ait.) established in 1933, and the other is jack pine (*Pinus banksiana* Lamb.) planted in 1966.

Indirect measurements of LAI in these two stands were made in September 1993 with two instruments, the PCA and the TRAC. The PCA was used to

determine the effect LAI L_e and the TRAC for the element-clumping index Ω_E . The TRAC consists of a quantum sensor (Li-Cor, Lincoln, Nebraska, Model LI-190SB, 10 μ s time constant) mounted at one end of a supporting arm and a data logger (Campbell Scientific, Logan, Utah, Model CR10) with a storage module (Model SM716). During measurements under cloudless conditions, the TRAC was hand carried at approximately 70 cm above the forest floor to obtain the total transmitted photosynthetic photon flux density (PPFD), in micromoles per square meter per second, 0.4–0.7 μ m) along a straight transect. The data logger sampled the quantum sensor output at a rate of 32 Hz. With a walking speed of 0.33 m/s, a sampling rate of approximately 100 readings/m was achieved. Before the measurements, marking flags were inserted on the floor every 10 m along the transect. At each flag, a pulse was sent to the data logger to register the distance by pressing a button on the supporting arm. In the red pine stand, two transects of 60 m each in the southeast–northwest direction were made for each set of measurements. In the jack pine stand, measurements were made on two transects of 50 m each in an approximately east–west direction. The TRAC was used on these transects on a clear day (16 September 1993). Six or seven equally spaced readings were taken with the PCA on each transect on an overcast day (17 September 1993). Two PCA instruments were used, one in the stands and the other at the center of an adjacent large clearcut (the tops of most surrounding trees were lower than 75° from the zenith). The latter was recording in a remote mode with a sampling rate of one reading per 15 s. Before the measurements, these two instruments were calibrated against each other following the procedures recommended by the LAI-2000 PCA Instruction Manual.¹⁸ In the subsequent calculation of L_e , readings of these two units were merged by the use of the standard software C2000.com provided by Li-Cor with the options ACT and no masking of the rings.

Destructive sampling of the two stands was performed in July 1992. Details of the sampling procedures are given in Deblonde *et al.*¹⁵ Briefly, four trees were felled in the red pine stand (referred to as RP02 in their paper) and two in the jack pine stand (JP01). The total leaf areas measured for the individual trees felled were extrapolated to LAI for the whole stand, based on a distribution of tree basal area and a measured relationship between sapwood area and basal area. The total needle area on a tree was obtained from the fresh weights of all branches on felled trees and subsamples of six branches per tree to obtain a relationship between the leaf area in a branch and the branch fresh weight. The needle surface area was measured with a camera–computer system (AgVision, Decagon Devices, Inc., P.O. Box 835, Pullman, Washington), and the projected area of needles laid flat and unconstrained (i.e., not pressed flat) was taken to be the one-sided area of the needles. In Deblonde *et al.*,¹⁵ LAI is defined as the total

one-sided needle area per unit ground surface area. Lang¹⁹ and Chen and Black¹ independently demonstrated that the correct definition of LAI is half the total leaf (needle) area per unit ground surface area. These two definitions are very different for conifer needles. In the present study, the ratio of half the total needle area to the projected area of an unconstrained horizontal needle was determined with the same AgVision system to be 1.62 ± 0.10 and 1.25 ± 0.10 for the jack pine and red pine species, respectively. This means that the value of LAI presented by Deblonde *et al.*¹⁵ was negatively biased by a factor of 1.62 and 1.25 for these two stands. These results could be explained by the shape of the needles for these species. Both jack pine and red pine needles are approximately hemispherical cylinders. Jack pine needles (approximately 35 mm long) are twisted and appear to be random in the angular position rotational about the long axis of the needle when laid freely on a flat surface. Red pine needles (120 mm long) are straight and easily laid flat on the large side. For horizontal needles with random rotations about their long axes, the ratio of half the total needle area to the projected area is $\pi/2$, i.e., 1.57.^{1,19} Therefore, the ratio is close to 1.57 for jack pine and considerably smaller than this value for red pine. The direct LAI values used in the present paper have been corrected with the two factors.

The ratio (γ_E) of leaf area to shoot area was also given for the stands by Deblonde *et al.*,¹⁵ who used the definition of the total one-sided (projected) area of needles in a shoot to the average shoot projected area in one direction.⁹ By this definition, shoots are treated as flat objects, but in reality the projection of shoots resembles spheres and cylinders, where their surfaces contribute to radiation interception in the canopy. Chen and Black¹⁰ and Fassnacht *et al.*¹⁴ proposed a new definition as follows:

$$\gamma_E = A_L/A_s, \quad (21)$$

where A_L is half the total of needle area in a shoot and A_s is half the total shoot area. If a shoot is approximated by a circular cylinder with a diameter of D and a length of L_s and flat ends, then $A_s = \pi(DL_s + 0.5D^2)/2$, which is half the total surface area of the cylinder. If the shoot projection can be approximated by a sphere, $A_s = 0.5\pi D^2$, which is half the total sphere surface area. We believe that the definitions of A_L , A_s , and γ_E as stated here are correct. It is demonstrated mathematically and numerically by Chen and Black¹⁰ that the projection of an object, when averaged for all angles of projection, is determined by half the total object surface area rather than the largest projected area. The PCA calculates LAI based on the principle established by Miller²⁰ and a technique developed by Lang.²¹ The LAI from the PCA is one half the total element surface area per unit ground surface area. Because for most conifer stands, shoots are identified as the foliage elements, the PCA in fact provides information on the shoot-area index for conifer canopies.

In the present study, the measurements of γ_E were repeated. We sampled 9 red pine shoots and 12 jack pine shoots at various heights from two codominant trees in each of the stands. The measurements were made with the AgVision system. The projected area of a shoot was measured with the shoot long axis arranged at three angles: horizontal, vertical, and 45° to the zenith. It was found that the projected shoot area does not change more than 7% and 25% for the red pine and the jack pine, respectively, when the angle of projection varied from horizontal to vertical with respect to the shoot long axis, and thus the shapes of the shoots were approximated by spheres. This means that A_s can be taken as $2A_{sp}$, where A_{sp} is the mean shoot projected area directly measured with the AgVision system. In the calculation, there is a multiplication factor of 2 because half the total surface area of a sphere is twice the projected area of the sphere. The measured values of γ_E are 2.07 and 1.30 for red pine and jack pine, respectively. The difference with the respective values of 2.66 and 2.08 found by Deblonde *et al.*¹⁵ results from two factors: (1) A_l in the new measurements is taken as half the total needle area rather than the projected area of unconstrained needles, and therefore it is larger than the previous values by a factor of 1.25 and 1.62 for red pine and jack pine, respectively. (2) A_s in the new measurements is twice as large as the projected shoot area (taken to be A_s in the old measurements). The combined effect of these two factors is to reduce γ_E by a factor of 1.60 for red pine and 1.23 for jack pine, but the corresponding differences in these two sets of data are 1.29 and 1.60, indicating considerable uncertainties in either or both of the measurements.

The contribution of woody materials above the ground was estimated by Deblonde *et al.*¹⁵ to be 9% and 20% of the LAI for red pine and jack pine, respectively, and their measurement of LAI (green leaves only) by destructive sampling was 4.9 for red pine and 1.6 for jack pine. The plant-area index is $4.9 \times 1.25 + 4.9 \times 0.09 = 6.56$ for the red pine stand and $1.6 \times 1.62 + 1.60 \times 0.2 = 2.9$ for the jack pine stand, where 1.25 and 1.60 are the correction factors, or the ratios of half the total needle area to the projected area of unconstrained horizontal needles. When the new values of γ_E and plant-area index are used, the ratio of the indirect to direct LAI values of Deblonde *et al.*¹⁵ changes from 2.03 to 0.81 for jack pine and 1.52 to 0.97 for red pine.

The mean projected areas (A_{sp}) of shoots measured in the present study are 21,517 mm² and 4430 mm² for the red pine and jack pine species, respectively. Since the shape of the shoots is approximated by spheres, the characteristic width of the shoots is taken to be $(\pi/4A_{sp})^{1/2}$ which is 130 mm for the red pine and 59 mm for the jack pine.

4. Results

A. Clumping Index

Figure 4 shows, as an example, a small section of a PPFd record measured in the red pine stand with

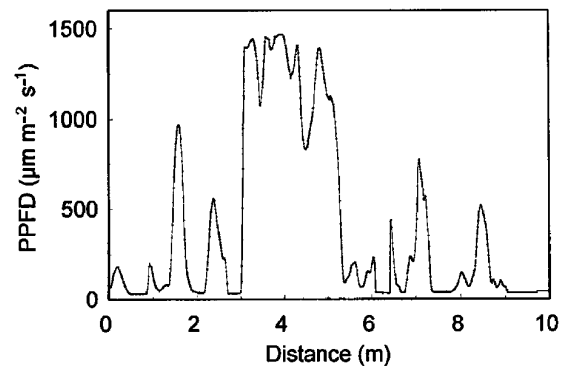


Fig. 4. Portion of instantaneous PPFd measured near noon on 16 September 1993 on a transect in a red pine stand. The measurement interval is 10.3 mm.

TRAC. The measurement interval was 10.3 mm. In the distribution of the measured total PPFd, there appears to be a steady baseline that indicates the diffuse component at approximately $55 \mu\text{mol m}^{-2} \text{s}^{-1}$. On this short transect, 21 sunflecks can be identified. Any significant increase (1%) in the PPFd value from the baseline or reversal of a decreasing trend indicates the beginning of a sunfleck. The end of a sunfleck is determined when either the PPFd reaches the base value or the beginning of a new sunfleck is detected. In the large sunflecks near the middle of the transect, the peak PPFd's minus the base value reach the maximum value (P_D), which is the direct component of the PPFd above the canopy. From the apparent sunfleck width and P_D , the corresponding canopy gap size can be calculated (Appendix B).

Figure 5 shows two examples of the gap-size distribution measured in the red pine stand. In Fig. 5(a) (case 1 in Table 1), the largest gap of size 740 mm and two relatively large gaps of size 455 mm and 380 mm are in excess of the first and second estimates of $F(\lambda)$, respectively (which are not shown in Fig. 5). After four iterations, the contribution of these gaps to the gap-fraction accumulation is largely reduced [only very small probabilities for these gaps, as determined by $F(\lambda)$, remain], and the canopy gap fraction reduces from 0.105 to 0.085, *i.e.*, $F_m(0) = 0.105$, $F_{mr}(0) = 0.085$, and $\Delta g = 0.02$. Using these values, it is calculated from Eq. (16) that $\Omega_E = 0.93$. There are small discrepancies between $F_{mr}(\lambda)$ and $F(\lambda)$ (≤ 0.01), indicating either errors in the gap-size measurements or the actual element size differing from 130 mm that is used in the calculation of $F(\lambda)$. However, the error in the final Ω_E resulting from the discrepancies is less than 3.5%. These discrepancies are the largest among all the cases shown in Table 1. Figure 5(b) (case 4 in Table 1) shows clearly that the three largest gaps of size 940, 490, and 340 mm would not have existed if the canopy were random. After three iterations, these three gaps were largely removed, and the canopy gap fraction was reduced from 0.0565 to 0.042, resulting in a Ω_E value of 0.91.

Figure 6 shows a similar result obtained from the jack pine stand. In this case almost all the gaps larger than 100 mm are removed after five iterations.

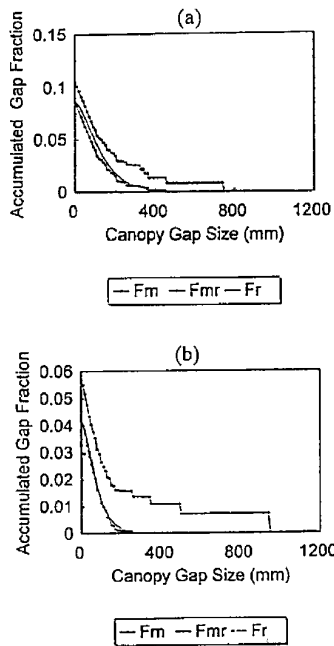


Fig. 5. Two gap-size distributions measured in a red pine stand (a) at a solar zenith angle $\theta = 44.0^\circ$, (b) at $\theta = 58.4^\circ$. A measured distribution $F_m(\lambda)$ is denoted by ■, the final distribution of $F_{mr}(\lambda)$ is denoted by ●, and $F(\lambda)$ is shown as a smooth curve.

After the removal, $F_{mr}(\lambda)$ resembles closely $F(\lambda)$ for a random canopy. With the gap fraction reduced from 0.043 to 0.027, the element-clumping index Ω_E is calculated to be 0.88.

B. Effect of Element Width

In the above gap-size analysis, the size of foliage elements has to be predetermined. To understand the importance of the choice of W , the element-clumping index was calculated at various input W_p values (Fig. 7). In both cases shown in Fig. 7 (for the jack pine stand the values are obtained from one gap-size distribution, and for the red pine stand the values are averages of cases 1–5 in Table 1), the element-clumping index increases with increasing input element size and becomes asymptotic at large input values. It is interesting to note that for both species the calculated clumping index reaches values close to the asymptote at inputs approximately equal to the element characteristic width, which is 130 mm for the red pine and 59 mm for the jack pine. This suggests that the calculation of Ω_E with a gap-size

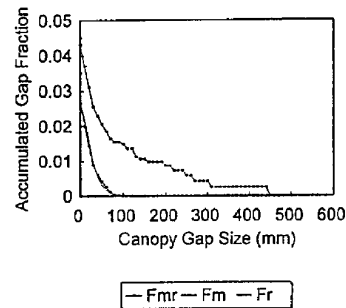


Fig. 6. Gap-size distributions measured in a jack pine stand at $\theta = 67.6^\circ$. A measured distribution $F_m(\lambda)$ is denoted by ■, the final distribution of $F_{mr}(\lambda)$ is denoted by ●, and $F(\lambda)$ is shown as a smooth curve.

distribution is not very sensitive to the choice of the element width within a reasonable range. It also suggests that it is possible to determine the characteristic element width from similar $W - \Omega_E$ curves. Figure 7 provides further justification for treating shoots of conifer species as foliage elements for radiation-interception considerations.

C. Plant-Area Index

Figure 8 shows measurements of the PCA on transects in both the jack pine and the red pine stands. The variation in L_e on the transects is very small, showing the homogeneity of the stand at large scales. Equally spaced PCA measurements were made along transects in the jack pine stand. Two of the transects were also used for TRAC measurements. These two transects were 50 m long and perpendicular to a road with a width of approximately 5 m and started from the road. The measured values at 0, 10, and 20 m from the road were relatively small compared with those at other locations, showing the effect of the road on the PCA measurements. These affected measurements were therefore not used in the calculation of the mean L_e value. To ensure that these smaller measurements were affected by the road, an additional transect that was parallel to the road and 30 m off the road was used for the PCA measurements. At this distance there was still some road effect but, judging from the variation in L_e on the 50-m transects, we believe that the effect was small. The small variation on the 60-m transect also indicates the homogeneity of the stand. The TRAC measurements were made when the Sun was on the

Table 1. Summary of TRAC Measurements

Case	Stand	EDT ^a	βt (°)	β_s (°)	θ (°)	$\Delta\beta$ (°)	W (mm)	W_p (mm)	Ω_E
1	red pine	1230–1235	145	168.7	44.0	23.7	130	168	0.93
2	red pine	1400–1409	145	201.4	44.9	56.4	130	141	0.98
3	red pine	1515–1520	145	224.2	52.2	79.2	130	131	0.87
4	red pine	1559–1607	145	235.9	58.4	90.0	130	130	0.91
5	red pine	1640–1646	145	244.8	64.2	99.8	130	132	0.87
6	jack pine	1700–1709	165	249.2	67.6	84.2	59	59	0.88

^aEastern daylight savings time.

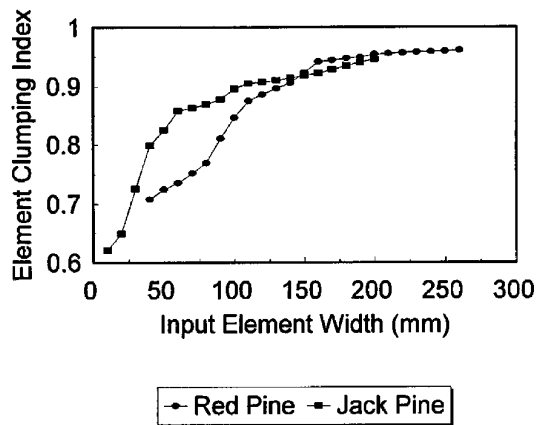


Fig. 7. Element-clumping index becomes asymptotic at large input element widths for both jack pine and red pine stands. The destructively measured widths were 59 mm and 130 mm for jack pine and red pine shoots, respectively.

same side of the road in the jack pine, and therefore the road effect was avoided. The mean values of L_e were 2.77 and 2.13 for red pine and jack pine stands, respectively.

Equation (20) was used to calculate the plant-area index L . For the red pine stand, $L = 2.77 \times 2.08/0.91 = 6.33$, where $L_e = 2.77$, the needle-shoot-area ratio $\gamma_E = 2.08$ [Eq. (19)], and the element-(shoot-) clumping index 0.91 is taken as the average values of Ω_E for cases 1–5 in Table 1. Correspondingly, for the jack pine stand, $L = 2.13 \times 1.3/0.88 = 3.15$, where $\Omega_E = 0.88$ for case 6 in Table 1. These indirect values of L compare well with the direct values obtained from destructive sampling (Fig. 9). The errors in both the direct and indirect measurements are estimated to be of the order of $\pm 15\%$. The error in the direct measurements involves uncertainties resulting from limited subsampling (number of trees felled, number of branches sampled, and number of needles measured). To calculate LAI for the whole stand, relationships between needle weight and area and between tree trunk or branch diameter and needle area have to be used. There are errors in each of the relationships. At the basic level, the

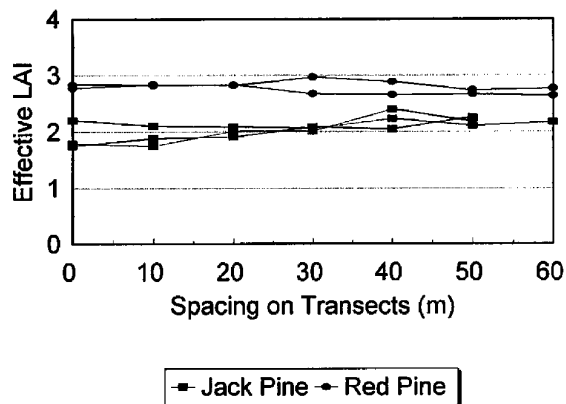


Fig. 8. Effective LAI (L_e) measured on transects in a jack pine and a red pine stand with the Li-Cor LAI-2000 Plant Canopy Analyzer.

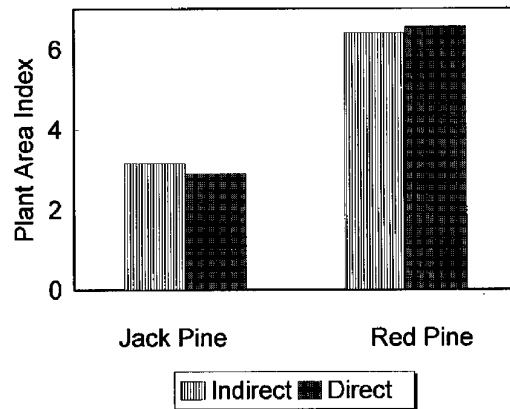


Fig. 9. Comparisons of indirect and direct measurements of plant-area index. The indirect measurements were obtained with the LAI-2000 Plant Canopy Analyzer and the Portram, and the direct measurements were obtained through destructive sampling.

measurement of needle area alone can have an error of $\pm 5\%$ or more. In the indirect measurements, the largest uncertainty is in the measurements of the needle-shoot-area ratio. This uncertainty can be reduced by increasing the sample volume. The error in measuring L_e with the PCA is small for canopies with low and moderate LAI, where the scattered light in the canopy is relatively small compared with the transmitted skylight. In both stands investigated here, L_e is small, and therefore the scattering effect is expected to be small. In many previous studies, the largest uncertainty in indirect measurements of LAI resulted from the unknown effect of nonrandom spatial distribution of foliage elements on the measurements. The element-clumping index derived from the gap-size distribution has greatly reduced, if not eliminated, the uncertainty. We, therefore, believe that with the utilization of canopy gap-size information, indirect measurements of LAI, or plant-area index in general, can be more accurate than partial direct measurements obtained through destructive sampling.

5. Discussion

In previous studies of radiation regimes in plant canopies, theories and instruments have often been tested in homogeneous canopies, with few exceptions. One of these is the research of Lang and Xiang,⁸ who developed a finite-transect-averaging technique for optical measurements of LAI in discontinuous canopies. By the use of this technique, LAI is calculated as the average of many LAI values measured on small transects 10 times the foliage-element width. This technique not only eliminates the need for spatial homogeneity, but also greatly reduces the effect of foliage clumping at large scales. However, the effect of nonrandomness within the small finite transect remains. When Lang and Xiang's⁸ technique is applied to TRAC data obtained in the red pine and the jack pine stands, it is found that calculated LAI values decrease monotonically (almost exponentially) with the increase in the length of the finite transect. If

shoots are treated as elements, the lengths of the finite transects must be 1.3 m and 0.6 m for the red pine and the jack pine stands, respectively. At these averaging lengths, the calculated values of LAI are 10% (for 1.3 m) and 16% (0.6 m) larger than those obtained with the whole transect as the averaging length; i.e., the shoot-clumping indices are 0.91 and 0.86 for the red pine and jack pine stands, respectively. These indices are in good agreement with those derived from gap-size analysis, indicating that the assumption of local randomness for shoot spatial distribution within the finite transect is reasonably good. However, if the value of 160 mm recommended by Lang *et al.*²² for the length of the finite transect is used, the clumping indices calculated similarly become 0.80 and 0.75 for the red pine and the jack pine stands, respectively. These values agree with neither the respective shoot-clumping indices Ω_E (0.91 and 0.88) nor the foliage-clumping indices Ω (0.44 and 0.68) given in this paper. This suggests that Lang and Xiang's method can be improved when the size of foliage elements and hence the required finite-transect length are correctly determined.

The gap-size analysis method presented in this paper is an improvement on the Lang and Xiang finite-transect method because it avoids the assumption of local randomness. Our numerical simulation reveals that this assumption can cause considerable errors under circumstances in which a canopy consists of distinct gaps and sections of foliage. One of the advantages of the gap-analysis method is that the computed element-clumping index is not very sensitive to the value of element width within a reasonable range, and the characteristic element width can be determined numerically through plots such as Fig. 7.

The two plantations studied here have nearly random distributions of foliage elements (shoots) because the element-clumping indices are close to unity. However, the small deviations from randomness are easily detected in gap-size distributions. This indicates that the gap-size-analysis method can be very reliable and promising for improving indirect measurements of LAI of plant canopies. Since no assumptions for the foliage spatial distribution are necessary in deriving the theory, the method can be used for all types of plant canopies.

In this paper, only clumped canopies are investigated. If foliage elements are regularly distributed in space, the value of Ω_E will be larger than unity. In this case, large gaps will appear at probabilities smaller than the predictions for a random canopy, and a gap-filling technique can be used to quantify Ω_E .

6. Conclusions

A new theory for gap-size analysis is presented in this paper to improve optical measurements of the leaf-area index (LAI) of plant canopies. In the theory, the element-clumping index quantifying the effect of

nonrandom spatial distribution of foliage elements is derived from the change in canopy gap fraction after the removal of large gaps appearing at probabilities in excess of predictions for a random canopy. This theory avoids making the assumption for a spatial-distribution pattern of foliage clumps used in the gap-size analysis by Chen and Black¹⁰ and therefore is applicable to a range of plant canopies, including forest plantations investigated here. A prototype sunfleck-LAI instrument named TRAC has been developed to measure the canopy gap-size distribution. The accuracy of deriving the element-clumping index from a gap-size distribution is approximately 97%. We believe that the methodology presented in this paper can be used for all heterogeneous canopies, including row crops, forest stands with natural and unnatural gaps, and sparse vegetation. In remote-sensing studies for large areas, a large quantity of the ground truth LAI data can be obtained quickly and accurately with TRAC in conjunction with the LAI-2000 PCA.

Appendix A: List of Symbols

A_L	Half the total needle area in a shoot
A_s	Half the total shoot area (if the projection of a shoot is approximated by sphere, it is twice the mean projected area of a shoot $\overline{A_{sp}}$)
$\overline{A_{sp}}$	Mean projected area of a shoot
c	Shape factor (ratio of W to w)
Δg	Total fraction of gaps truncated
$G(\theta)$	Projection of unit leaf area on a plane perpendicular to the direction θ
L	Plant-area index or LAI when woody materials are ignored
L_E	Element-area index
L_e	Effective LAI as measured with the PCA
L_p	Projected element-area index
L_t	Length of measuring transect
w	Element width in the direction perpendicular to the transect
W	Characteristic element width
W_p	Element width projected on a horizontal surface in the transect direction
$F(\lambda)$	Canopy gap-size distribution for a random distribution of the spatial position of foliage elements
$F_m(\lambda)$	Measured canopy gap-size distribution
$F_{mr}(\lambda)$	Measured canopy gap-size distribution after processing to resemble $F(\lambda)$
$\Delta\beta$	Difference between azimuth angles of the Sun and the transect
β_t	Azimuthal angle of the transect
γ_E	Ratio of half the total leaf (needle) area in a shoot to half the total shoot area, A_L/A_s
λ	Canopy gap size
θ	solar zenith angle
θ_p	Width projection angle depending on θ and $\Delta\beta$
ρ	Number of foliage elements per unit ground surface area

- σ Foliage-element area
- Ω Clumping index for leaves (needles)
- Ω_E Clumping index for elements (shoots)

Appendix B: Gap Size from a Sunfleck

On the Earth's surface, the Sun appears to be a disk of angular radius 0.0047 rad, or 16'. Since the Sun is not a point source of light, it causes the penumbra effect: it casts shadows with fuzzy edges, which are approximately 94 mm in width for an object 10 m away from the shadow. In Fig. 10, a canopy gap at some height results in a sunfleck on the surface with a width much larger than the gap because of the penumbra effect. If the gap width is smaller than the apparent size of the solar disk, the maximum light level in the sunfleck is less than the value above the gap because the sunlit area is not fully exposed to the Sun. Based on the mass conservation principle, the total number of photons reaching at the surface in the sunfleck should equal the total number passing through the gap, since there is no photon absorption between the gap and the surface. The total number of photons passing through the gap in unit time is

$$S1 = \lambda P_D, \quad (B1)$$

where P_D is the direct component of the PPFD above the canopy and is obtained in the center of a large gap where the penumbra effect does not exist. The total number of photons reaching the surface in unit time is

$$S2 = \int_0^{\lambda_s} P(x) dx \quad (B2)$$

where $P(x)$ is the direct PPFD component measured at location x within the sunfleck and λ_s is the apparent sunfleck width. Since $S1 = S2$ (mass conservation),

$$\lambda = \frac{1}{P_D} \int_0^{\lambda_s} P(x) dx. \quad (B3)$$

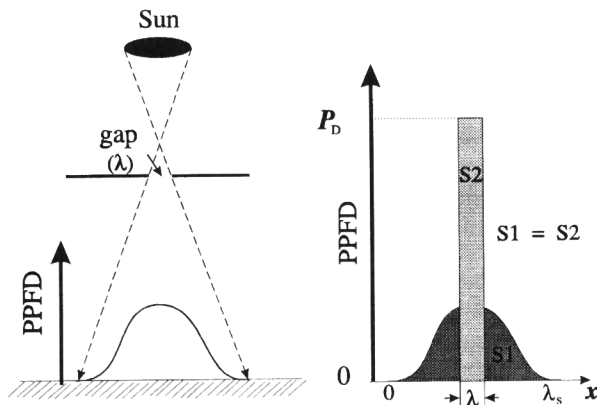


Fig. 10. Sunlight distribution in a sunfleck resulting from a canopy gap of size λ , where P_D is the level of direct PPFD above the canopy.

The shape of the PPFD distribution within different sunflecks varies in plant canopies. This is due not only to the variation in the height of canopy gaps, but also the variation in the vertical shape of the gaps. In the derivation of Eq. (B3), it is assumed that the gap has only a very small vertical thickness to ensure that the absorption of light on the imaginary wall of the gap is negligible. In reality, a canopy gap may be overlaid by other gaps, and the gap has a certain thickness. The complexity of the canopy gap morphology may be approximated with vertical curvatures of the gap edges, which can be inferred from the shape of the PPFD distribution in a sunfleck. Tentative research in this direction shows that the calculated canopy gaps with the consideration of the curvatures are slightly larger than those of calculations with Eq. (B3). The difference is considerable only for gaps less than 30 mm. With the consideration of the curvatures, some improvements on the gap-size distribution are found at small λ values.

Appendix C: Characteristic Width

Spheres

In the present study, the shape of foliage elements (shoots) is approximated by spheres. A sphere under the Sun casts an elliptical shadow on the surface if the Sun is not at the zenith (Fig. 11). The short axis ($2a$) of the shadow equals the diameter (D) of the sphere, and the long axis ($2b$) is given by $D/\cos \theta$. For a transect traversing through the center of the shadow at an azimuthal angle $\Delta\beta$ relative to the long axis, i.e., the Sun's direction, the width (\overline{AB}) of the shadow on the transect is

$$\overline{AB} = 2(x_1^2 + y_1^2)^{1/2}, \quad (C1)$$

where (x_1, y_1) is one of the transect-ellipse crossing points A and B. We obtain the points by solving the following set of two equations:

$$\frac{x^2}{\left(\frac{D}{2 \cos \theta}\right)^2} + \frac{y^2}{\left(\frac{D}{2}\right)^2} = 1, \quad (C2)$$

$$y = x \tan \Delta\beta. \quad (C3)$$

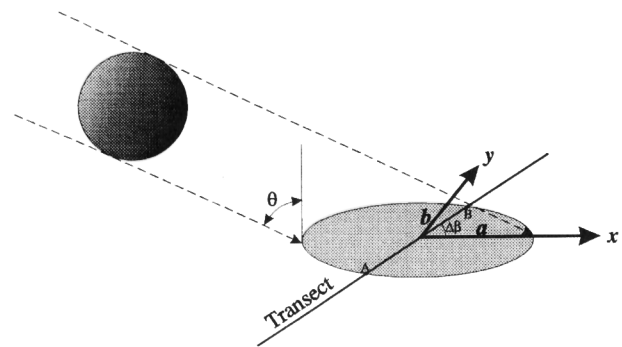


Fig. 11. Projection of a sphere representing a conifer shoot on a horizontal surface.

From Eqs. (C1)–(C3), it can be derived that

$$\overline{AB} = D \left(\frac{1 + \tan^2 \Delta\beta}{\cos^2 \theta + \tan^2 \Delta\beta} \right)^{1/2}. \quad (\text{C4})$$

In the same transect direction, the shadow width varies depending on the position of the transect relative to the center of the shadow, with \overline{AB} being the largest. To avoid unnecessary complications in deriving the mean, \overline{AB} is taken to be the representative width in a given direction, and the mean width W_p in Eq. (16) for the direction is \overline{AB} scaled down by a factor of $\pi/4$ similar to the case for spheres.¹⁰ Since $\overline{W} = \pi/4D$ and $W_p = \overline{W}/\cos \theta_p$ [Eq. (6)], it can be shown that

$$\cos \theta_p = \left(\frac{\cos^2 \theta + \tan^2 \Delta\beta}{1 + \tan^2 \Delta\beta} \right)^{1/2}. \quad (\text{C5})$$

This ensures that $W_p = W/\cos \theta$ at $\Delta\beta = 0$ and $W_p = W$ at $\Delta\beta = \pi/2$.

Cylinders

The shadow of a vertical cylinder is a long strip with a width equal to the diameter (D) of the cylinder and a length H_p equal to $H \tan \theta$, where H is the height of the cylinder. If $\Delta\beta \geq \tan^{-1}(D/H_p)$, the projected width W_p is then

$$W_p = \frac{W}{\sin \Delta\beta}. \quad (\text{C6})$$

This case applies to tree trunks in the present study. Many conifer tree crowns may also be approximated as cylinders.

This work is supported by a research grant from the Canada Centre for Remote Sensing (CCRS). Z. Li of CCRS assisted in part of the field data collection, and M. Penner of the Petewawa National Forestry provided logistic support.

References

1. J. M. Chen and T. A. Black, "Defining leaf area index for non-flat leaves," *Plant Cell Environ.* **15**, 421–429 (1992).
2. M. A. Spanner, L. L. Pierce, D. L. Peterson, and S. W. Running, "Remote sensing temperate coniferous forest leaf area index: the influence of canopy closure, understory and background reflectance," *Int. J. Remote Sensing* **11**, 95–111 (1990).
3. M. A. Spanner, L. L. Pierce, S. W. Running, and D. L. Peterson, "The seasonal trends of AVHRR data of temperate coniferous forests: relationship with leaf area index," *Remote Sensing Environ.* **33**, 97–112 (1990).
4. B. Leblon, H. Granberg, C. Anseau, and A. Royer, "A semi-empirical model to estimate the biomass production of forest canopies from spectral variables part 1: relationship between spectral variables and light interception efficiency," *Remote Sensing Rev.* **7**, 109–125 (1993).
5. H. L. Gholz, F. K. Fitz, and R. H. Waring, "Leaf area differences associated with old-growth forest communities in the western Oregon Cascades," *Can. J. For. Res.* **6**, 49–57 (1976).
6. N. J. Smith, "Estimating leaf area index and light extinction coefficients in stands of Douglas-fir," *Can. J. For. Res.* **30**, 317–321 (1993).
7. J. Welles, "Some indirect methods of estimating canopy structure," in *Instrumentation for Studying Vegetation Canopies for Remote Sensing in Optical and Thermal Infrared Regions*, J. Norman and N. Geol, eds. (Harwood, London, 1990), pp. 31–43.
8. A. R. G. Lang and Y. Xiang, "Estimation of leaf area index from transmission of direct sunlight in discontinuous canopies," *Agric. For. Meteorol.* **37**, 229–243 (1986).
9. S. T. Gower and J. M. Norman, "Rapid estimation of leaf area index in forests using the LI-COR LAI-2000," *Ecology* **72**, 1896–1900 (1991).
10. J. M. Chen and T. A. Black, "Foliage area and architecture of plant canopies from sunfleck size distributions," *Agric. For. Meteorol.* **60**, 249–266 (1992).
11. H. H. Neumann, G. den Hartog, and R. H. Shaw, "Leaf area measurements based on hemispheric photographs and leaf-litter collection in a deciduous forest during autumn leaf-fall," *Agric. For. Meteorol.* **45**, 325–345 (1989).
12. E. E. Miller and J. M. Norman, "A sunfleck theory for plant canopies. I: Lengths of sunlit segments along a transect," *Agron. J.* **63**, 735–738 (1971).
13. M. Monsi and T. Saeki, "Über den Lichtfaktor in den Pflanzengesellschaften und Seine Bedeutung für die Stoffproduktion," *Jpn. J. Bot.* **14**, 22–52 (1953).
14. K. Fassnacht, S. T. Gower, J. M. Norman, and R. M. McMurttrie, "A comparison of optical and direct methods for estimating foliage surface area index in forests," *Agric. For. Meteorol.* **71**, 183–207 (1994).
15. G. Deblonde, M. Penner, and A. Royer, "Measuring leaf area index with the LI-COR LAI-2000 in pine stands," *Ecology* **75**, 1507–1511 (1994).
16. T. Nilson, "A theoretical analysis of the frequency of gaps in plant stands," *Agric. Meteorol.* **8**, 25–38 (1971).
17. J. M. Chen, T. A. Black, and R. S. Adams, "Evaluation of hemispherical photography for determining plant area index and geometry of a forest stand," *Agric. For. Meteorol.* **56**, 129–143 (1991).
18. *LAI-2000 PCA Operating Manual* (Li-Cor, Inc., Lincoln, Neb., 1991).
19. A. R. G. Lang, "Application of some of Cauchy's theorems to estimation of surface areas of leaves, needles and branches of plants, and light transmittance," *Agric. For. Meteorol.* **55**, 191–212 (1991).
20. J. B. Miller, "A formula for average foliage density," *Aust. J. Bot.* **15**, 141–144 (1967).
21. A. R. G. Lang, "Simplified estimate of leaf area index from transmittance of the Sun's beam," *Agric. For. Meteorol.* **41**, 179–186 (1987).
22. A. R. G. Lang, R. E. McMurttrie, and M. L. Benson, "Validity of surface area indices of *Pinus radiata* estimated from transmittance of the Sun's beam," *Agric. For. Meteorol.* **57**, 157–170 (1991).