A NEW OPTICAL INSTRUMENT FOR MEASURING LEAF AREA INDEX BASED ON A CANOPY GAP SIZE DISTRIBUTION THEORY

Jing M. Chen

Canada Centre for Remote Sensing
#419-588 Booth Street
Ottawa, Ontario
Canada K1A 0Y7

1. INTRODUCTION

Commercially available optical instruments for measuring LAI are all based on the gap fraction principle. These instruments include LI-COR LAI-2000, Demon and Sunfleck Ceptometer. They calculate LAI from canopy gap fraction (radiation transmittance) under the assumption of the random spatial distribution of leaves. Plant canopies are generally not random, especially in the case of forest stands with highly organized (clumped) foliage, causing large errors in LAI measurements using these instruments.

The nonrandomness of foliage spatial distribution can be assessed from the canopy gap size distribution. Gap size refers to the physical dimension of gaps, while gap fraction can be defined as the percentage of sky seen from underneath the canopy. For the same gap fraction, there can be different gap size distributions. A new optical instrument named Tracing Radiation and Architecture of Canopies (TRAC) is designed to measure the canopy gap size using a mobile light sensor sampled at a high frequency. A new gap size distribution theory based on Miller and Norman (1971) is developed to quantify the effect of nonrandom foliage spatial distribution on LAI measurements. A technique has been developed to compute the foliage clumping index from a measured canopy gap size distribution.

TRAC was developed at the Canada Centre for Remote Sensing by the author and has been tested in several boreal forest stands. LAI results from these stands as part of the Boreal Ecosystem-Atmosphere Study (BOREAS) have been obtained using TRAC (Chen and Cihlar 1995b, Chen 1995). With the utilization of gap size information by TRAC, it is found that optical measurements of LAI in forest stands can be more accurate than allometric methods obtained from partial destructive sampling. To measure LAI over large areas for validating remote sensing algorithms, a combined use of TRAC for foliage spatial distribution and LAI-2000 for foliage angular distribution is suggested.

2. PROTOTYPE TRAC

Figure 1. The prototype TRAC (Tracing Radiation and Architecture of Canopies)

The prototype TRAC (Fig. 1) consists of three quantum sensors (LI-COR, Lincoln, NE, Model LI-190SB, 10 ms time constant), a data logger (Campbell Scientific, Logan, UT, Model CR10) and a storage Module (Model SM716). Two of the sensors faced upwards to measure the downwelling total and diffuse photosynthetically active radiation (PAR), and one faced downward to measure the reflected PAR from the forest floor. The measurements from the downward-facing sensor are used for estimating the PAR absorbed by the canopy. For the diffuse sensor, a vertical shading strip was used on the side to obstruct the direct light. The sensors were supported by a holding arm and connected to the data logger operated at a sampling frequency of 32 Hz. The whole system was hand-carried by a person walking along pre-established transects. With a walking pace of 1 m per three seconds, a sampling interval of 10 mm for each sensor could be achieved. During measurements, the operator needed to control the pacing while watching a leveling bubble and the shading to the diffuse sensor simultaneously. A button on the holding arm is used to register the distance on the data logger at pre-set distance marks along the transect.

The instrument is most suitable to tall canopies such as forests and plantations, but can also be used for agricultural crops where traversing of the instrument near the ground surface is possible. However, the principle described in this paper is applicable to any plant canopies.

3. EXAMPLE OF TRAC DATA

Figure 2 shows an example of the raw data acquired using TRAC in a mature jack pine stand located near Candle Lake, Saskatchewan, which is one of BOREAS tower flux sites. These instantaneous measurements exhibit the canopy architecture through the variations in the gap size. The large flat-topped spikes indicate large gaps while small sharp spikes are associated with small gaps in the canopy in the sun's direction. The record contains gaps of all sizes (from a few mm to several meters). The size of the gaps can be calculated after considering the penumbra effect (Chen and Black 1992). Usually an 100-300 m transect is required to characterize a forest stand.

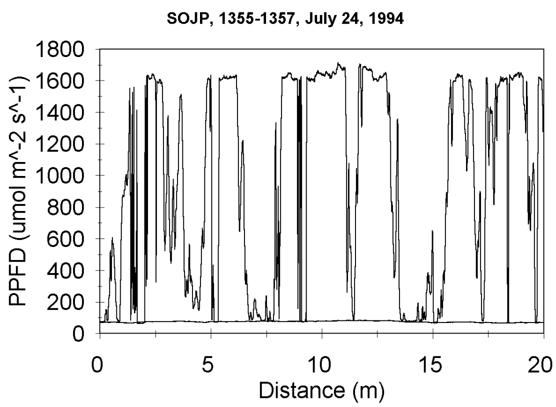

Figure 2. A section of a TRAC record of photosynthetic photon flux density (PPFD) taken in a mature jack pine stand. The flat bottom line indicates the level of diffuse PPFD near the forest floor.

4. THEORY

The gaps along the transect can be sorted in descending order according to their size. The complete theory for calculating the clumping index is presented in Chen and Cihlar (1995a), but is briefly described here. From the sorted gap size series, a gap size distribution curve $F_m(\lambda)$ can be formed, where $F_m(\lambda)$ is the fraction of gaps larger than or equal to the gap size l. For a canopy with a random spatial distribution of foliage elements, the gap accumulation curve denoted by $F(\lambda)$ is predicted by

$$F(\lambda) = (1 + L_p \frac{\lambda}{W_{ep}}) e^{-L_p (1+\frac{\lambda}{W_{ep}})} \qquad (1)$$

where $L_{Ep} = \dfrac{G(\theta) L_E}{\cos\theta}$ (2)In eqs. (1) and (2), L_E is the foliage element (shoot) area index defined as half the total element area per unit ground surface area, W_{Ep} is the mean projected width of the element along the direction of the transect. In conifer canopies, the small gaps within a shoot can not be detected by TRAC because of the penumbra effect, and therefore the element is treated as the shoot (the basic collection of needles). In broadleaf canopies, leaves are considered as the elements. These are the only two parameters controlling the gap size distribution in the canopy. When the canopy is not random, the measured distribution curve $F_m(\lambda)$ deviates from $F(\lambda)$. If the canopy is clumped with respect to tree crowns and branches, the probability of seeing large gaps dramatically increased from the predictions for random canopies. The excessively large gaps can therefore be identified by comparing $F_m(\lambda)$ with $F(\lambda)$, and the contributions of the large gaps due to clumping can be removed from the gap accumulation. After the removal of all gaps in excess of $F(\lambda)$, the canopy is compacted and becomes pseudo random. The measured total canopy gap fraction is then reduced from $F_m(0)$ to $F_{mr}(0)$, where $F_{mr}(\lambda)$ is $F_m(\lambda)$ brought to the closest agreement with $F(\lambda)$ through the gap removal procedure. The element clumping index is then calculated as

$$\Omega_E = \frac{(1+\Delta g) \ln[F_m(0)]}{\ln[F_{mr}(0)]} \qquad (3)$$

where Δg is the total gap fraction removed and is $F_m(0)$ - $F_{mr}(0)$. In the gap removal procedure, $F(\lambda)$ is calculated first. The calculation requires both W_{Ep} and L_p. While W_{Ep} can be obtained from shoot analysis, L_p is unknown. Chen and Cihlar (1995a) developed an iteration procedure which avoids the prior knowledge of L_p. In the iteration, L_p is equal to -ln[$F_{mr}(0)$], where $F_{mr}(0)$ is first taken as $F_m(0)$, and a precursory $F(\lambda)$ is calculated as the first basis for gap removal. As the largest gaps are removed, $F_{mr}(0)$ decreases and L_p increases. The iteration proceeds by refining L_p and ceases when L_p reaches an asymptotic value or when part of $F_{mr}(\lambda)$ becomes smaller than $F(\lambda)$.

When Ω_E is obtained, LAI, denoted by L, can be calculated from

$L=(1-\alpha)\, L_e*\gamma_E/\,\Omega_E$

where L_e is the effective LAI calculated based on the gap fraction such as the direct readings of LAI-2000. α is the contribution of the woody material to the total above ground green and non-green areas. γ_E quantifies the effect of foliage clumping within the element, which is taken as the shoot for conifer species. For deciduous species, the elements are the leaves and γ_E is unity. TRAC is designed to quantify Ω_E only.

5. RESULTS

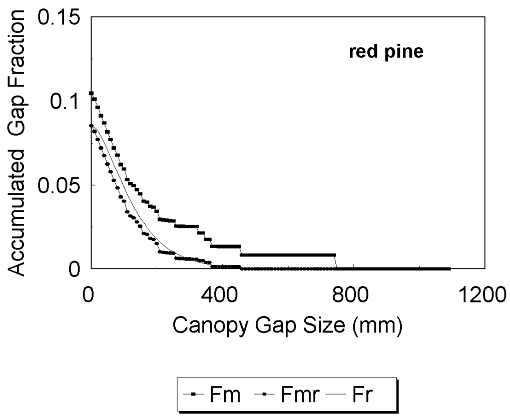

Figure 3. Gap size distribution in a red pine stand, where Fm is the measured distribution, Fr represents the random case, and Fmr is Fm brought to the closest agreement with Fr after a gap removal procedure.

Figure 3 shows measured and processed canopy gap size distributions in a red pine plantation near Patawawa, Ontario. The characteristic width of red pine shoots was measured to be 130 mm. The distribution of the shoots in this plantation was very close to the random case: only a few large gaps over a 50 m transect appeared at probabilities larger than the prediction for the random case. After the removal of the contribution of these large gaps (or portions of them) to the total canopy gap fraction, the measured curve ($F_{mr}(\lambda)$) agrees very well with the curve $F(\lambda)$ for the random case. The clumping index calculated using Eq. 3 is 0.93, i.e. the effect of foliage clumping at scales larger than the shoot only resulted in a decrease in the LAI measurement by 7% compared with the random case.

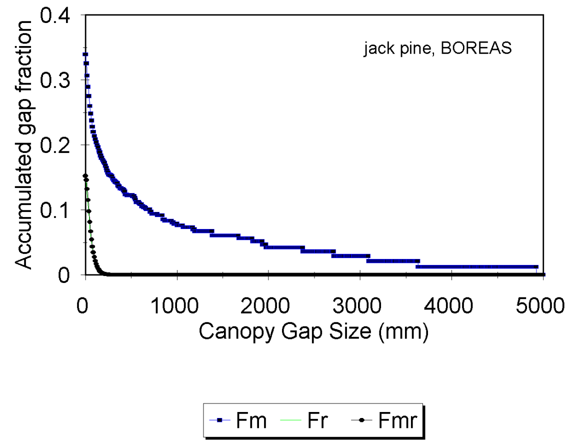

Figure 4. Gap size distribution in a jack pine stand. (See Figure 3 for the definitions of the curves.)

Figure 4 shows the similar results obtained in the mature jack pine stand (same as that in Fig. 2). Boreal forests are often very open, so was this stand. The largest gap observed over a 200 m transect was over 4800 mm (4.8 m). There were also many gaps larger than 200 mm. All these gaps appeared at probabilities in excess of the random case and were removed after applying the gap removal procedure, indicating that there would have been little probability of observing sunfleck on the forest floor larger than 200 mm if the shoots were randomly distributed in space. Many of the observed large gaps resulted from tree crown and branch architecture. The calculated element clumping index was 0.68 in this case, i.e. the grouping of shoots into branches and shoots made the apparent leaf area about 30% smaller. The element (shoot) width in this case was 60 mm.

Fig. 5 shows results from a mature aspen stand, a BOREAS tower flux site located in the Prince Albert National Park in Saskatchewan. The characteristic width of the broad leaves was taken to be 50 mm for the gap removal procedure. In the 100 m transect, there were many large gaps resulting from the grouping of foliage into tree crowns. After the removal of these gaps, the total canopy gap fraction is drastically reduced. The clumping index was determined to be 0.72.

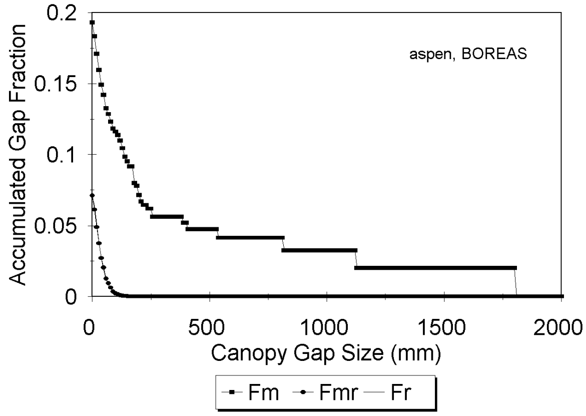

Figure 5. Gap size distribution in an aspen stand. (See Figure 3 for the definitions of the curves.)

6. DISCUSSION

For broadleaf canopies, the element clumping index includes the effect of foliage clumping at all scales, but for conifer canopies, it excludes the effect of within-shoot clumping because gaps between needles are often too small to be detected using the sun's beam as the probe. The within-shoot clumping effect can be estimated from analyzing shoot samples in laboratory (Chen and Black 1992, Fassnacht et al. 1995). This clumping factor does not vary very much between species and ages (Chen 1995), and a constant factor of 1.4 may be used for conifer canopies. This further increases LAI values by 40%.

It has been found by Chen and Cihlar (1995a) that results of LAI using the combination of LAI-2000 for foliage angle distribution and TRAC for foliage spatial distribution agree very well with destructive sampling results.

The gap size information can be used to derive several canopy architectural parameters useful for modeling radiation environment in plant canopies (Chen and Black, 1992 and Chen and Cihlar, 1995b).

For canopies with regularly spaced foliage elements (very rare cases), a gap filling technique can be used to derive the clumping index larger than 1.

7. CONCLUSIONS

As evident from the comparisons between the measured and random gap size distributions, the assumption of random foliage spatial distribution can cause large errors in LAI from optical instruments based on the gap fraction principle. The gap size information can be utilized to improve the measurements of LAI.

8. REFERENCE

Chen, J. M., 1995: Optically-based methods for measuring seasonal variation in leaf area index in boreal conifer stands. *Agric. For Meteorol.* (in press).

Chen, J. M., and T. A. Black, 1992: Foliage area and architecture of plant canopies from sunfleck size distributions. *Agric. For. Meteorol.*, **60**, 249-266.

Chen, J. M. and J. Cihlar, 1995a: Plant canopy gap size analysis theory for improving optical measurements of leaf area index of plant canopies. *Applied Optics* (to appear 20 September).

Chen, J. M. and J. Cihlar, J., 1995b: Quantifying the effect of canopy architecture on optical measurements of leaf area index using two gap size analysis methods. *IEEE Trans. Geosci Remote Sens*. **33**, 777-787.

Fassnacht, K., S. T. Gower, J. M. Norman, and R. E. McMurtrie, 1994: A comparison of optical an direct methods for estimating foliage surface area index in forests. *Agric. For. Meteorol.*, **71**, 183-207.

Gower, S. T., and J. M. Norman, 1990: Rapid estimation of leaf area index in forests using the LI-COR LAI-2000. *Ecology* **72**:1896-1900.

Miller, E. E., and J. M. Norman, 1971: A sunfleck theory for plant canopies. I. Lengths of sunlit segments along a transect. *Agron. J*. **63**, 735-738