Correction to the plant canopy gap-size analysis theory used by the Tracing Radiation and Architecture of Canopies instrument

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Abstract

A plant canopy gap-size analyser, the Tracing Radiation and Architecture of Canopies (TRAC) developed by Chen and Cihlar (Applied Optics, vol. 34, No. 27, pp. 6211-6222, 1995) and commercialized by 3rd Wave Engineering (Nepean, Canada) has been used around the world to quantify the fraction of photosynthetically active radiation absorbed by plant canopies, the leaf area index (LAI), and canopy architectural parameters. The TRAC is walked along transects under a canopy to measure sunflecks that are converted into a gap size distribution. A numerical gap removal technique is performed to remove gaps that are not theoretically possible in a random canopy. The resulting reduced gap size distribution is used to quantify the heterogeneity of the canopy and to improve LAI measurements. It is explicitly shown here that the original derivation of the clumping index was missing a normalization factor. For very clumped canopy with large gap fraction, the resulting LAI can be more than 100% smaller than previously estimated. A test case is used to demonstrate that the new clumping index derivation allows a more accurate change of LAI to be measured.

Introduction

The Tracing Architecture and Radiation of Canopies (TRAC) instrument, developed at Canada Centre for Remote Sensing, by Chen and Cihlar[1] and commercialized by 3rd Wave Engineering (Nepean, Canada) is an optical instrument used in leaf area index (LAI) estimation of plant canopies. Compared to other instruments such as the LAI-2000 (LI-COR), the TRAC uses not only the gap fraction, but also the gap size distribution. When the gap fraction alone is used to estimate LAI, an assumption of random foliage distribution is needed. The TRAC is walked along transects under canopies using the solar beam as a probe, recording the photosynthetic photon flux density (PPFD) at a high frequency (32 Hz) to estimate the gap size distribution. The TRAC can detect gaps as small as one millimetre for plant canopies once penumbra and multiple scattering effects are considered.

Theory and correction

For simplicity, the non-leaf material (e.g. woody material) is neglected here. The canopy gap fraction can then be related to the fraction of canopy openings (gap fraction) at a specific zenith angle, θ, with a modification of Beer's law[2]:

$$P_c(\theta) = e^{-G(\theta)\Omega_E(\theta)L/\cos(\theta)}, \qquad (1)$$

where $P_c(\theta)$ is the gap fraction for the clumped canopy, $G(\theta)$ is the foliage projection coefficient characterizing the foliage angular distribution, L is the leaf area index (LAI); and $\Omega_E(\theta)$ is a clumping index parameter determined by the spatial distribution pattern of the foliage elements (leaves for deciduous and shoots for conifers). A random canopy has $\Omega_E(\theta)$ equal to unity, while clumped canopies have $\Omega_E(\theta)$ less than unity. The product of L and $\Omega_E(\theta)$ is usually referred as the effective LAI $L_e(\theta)$ [3]. The clumping index of the foliage elements is:

$$\Omega_E(\theta) = \frac{L_e(\theta)}{L} = \frac{\ln[P_c(\theta)]}{\ln[P_R(\theta)]}, \qquad (2)$$

where $P_R(\theta)$ is the gap fraction of a canopy with the same LAI as the clumped canopy, but without any spatial clumping. $P_c(\theta)$ is easily estimated with plant canopy analysers or hemispherical photographs, but $P_R(\theta)$ is the gap fraction of an imaginary stands and thus cannot be directly measured. To estimate the clumping index, a theory based on gap size distribution has been developed[1,3]. Assuming a canopy of randomly distributed foliage element, the probability of having gaps larger than a length λ can be described with the accumulated gap fraction at a given zenith angle (Chen and Cihlar[1], modified from Miller and Norman[4]):

$$F(\lambda,\theta)=\left[1+L_p(\theta)\frac{\lambda}{W_p(\theta)}\right]e^{-L_p(\theta)\cdot[1+\lambda/W_p(\theta)]}, \quad (3)$$

where $W_p(\theta)$ is the mean width of the shadow of a foliage element projected on a horizontal surface perpendicular to θ; and $L_p(\theta)$ is the LAI projected onto the horizontal from the direction θ. The measured accumulated gap fraction is denoted $F_m(\lambda,\theta)$. At $\lambda = 0$, $F_m(0,\theta)$ is the gap fraction of the canopy ($P_c(\theta)$). Using a gap removal technique on $F_m(\lambda,\theta)$ that removes gaps not expected in a random canopies, a reduced accumulated gap fraction $F_{mr}(\lambda,\theta)$ similar to a random canopy $F_r(\lambda,\theta)$, can be obtained[1]. $F_{mr}(0,\theta)$ is not exactly $P_R(\theta)$ since the removed gaps create (correspond may be a better word) a compacted canopy, so Chen and Cihlar[1] derived the clumping index as:

$$\Omega_E(\theta)=\frac{\ln[F_m(0,\theta)]}{\ln[F_{mr}(0,\theta)]}\cdot[1+F_m(0,\theta)-F_{mr}(0,\theta)] \quad (4)$$

It will be shown here that the factor added ($F_m(0,\theta)$-$F_{mr}(0,\theta)$), to compensate for the gaps removal, needs to be normalized.

Assuming a transect of length x_1+x_2 (see Figure 1) in which segment 1 has a perfectly random distribution of LAI denoted L_1, and a segment 2 with a LAI of L_2 equal to zero. The LAI of the transect is then the weighted mean of the two different segments:

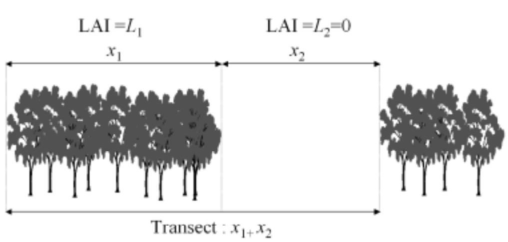

Figure 1: Representation of a forest stand where a large gap is found randomly in an otherwise randomly distributed forest canopy.

$$L=\frac{L_1\cdot x_1+L_2\cdot x_2}{x_1+x_2}=L_1\frac{x_1}{x_1+x_2} \quad (5)$$

It is assumed that segment one is long enough to statistically get a gap fraction as $P_1(\theta)=\exp[-G(\theta)L_1/\cos(\theta)]$. For the second segment, P_2 equals unity since there is no foliage present. The measured accumulated gap size distribution at $F_m(0,\theta)$ is the mean gap fraction of the transect at zenith angle θ :

$$F_m(0,\theta)=P_C(\theta)=\frac{P_1(\theta)x_1+x_2}{x_2+x_1}. \quad (6)$$

From Beer's law, the effective LAI at θ is computed as

$$L_e(\theta)=-\frac{\cos(\theta)}{G(\theta)}\ln[F_m(0,\theta)]. \quad (7)$$

When using a gap removal technique, it implies that $F_{mr}(0)$ is equal to $P_1(\theta)$ which yields

$$L_1=-\frac{\cos(\theta)}{G(\theta)}\ln[P_1(\theta)]=-\frac{\cos(\theta)}{G(\theta)}\ln[F_{mr}(0,\theta)]. \quad (8)$$

The clumping index is then:

$$\Omega_E(\theta)=\frac{L_e(\theta)}{L}=\frac{\ln[F_m(0,\theta)]}{\ln[F_{mr}(0,\theta)]}\cdot\left(1+\frac{x_2}{x_1}\right). \quad (9)$$

Using Eq. (6) and replacing $P_1(\theta)$ by $F_{mr}(0,\theta)$, x_2/x_1 is found:

$$\frac{x_2}{x_1}=\frac{[F_m(0,\theta)-F_{mr}(0,\theta)]}{[1-F_m(0,\theta)]}. \quad (10)$$

The clumping index can be written as

$$\Omega_E(\theta)=\frac{\ln[F_m(0,\theta)]}{\ln[F_{mr}(0,\theta)]}\cdot\left[1+\frac{F_m(0,\theta)-F_{mr}(0,\theta)}{1-F_m(0,\theta)}\right]. \quad (11)$$

Eq. (11) gives a clumping index larger than the previous solution (Eq. 4). The difference comes from the factor 1-$F_m(0,\theta)$, which is the non gap proportion of the canopy at θ.

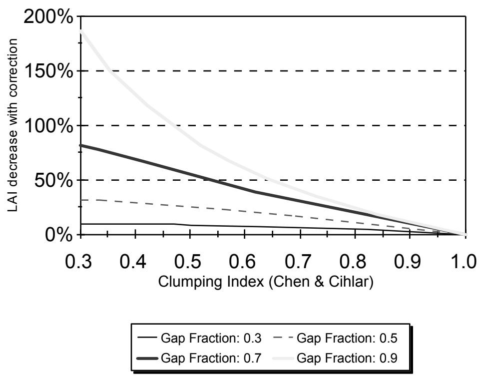

Figure 2: Effect of the correction on LAI estimation as a function of uncorrected clumping index. The thick grey line represents the worst-case scenario.

For dense canopies at any θ and for most canopies at large θ, the change is small between the two ways of calculating the clumping index. Figure 2 shows that if the gap fraction is large at θ on the transect, the correction can yield an LAI smaller than previously found by more than 100%. This is in accordance with Law *et al.*[5] who showed that the clumping index from TRAC resulted in good LAI estimations for all their plots, except for a clumped open stand.

To validate the new derivation of the clumping index, measurements taken in plantations with known percentage of LAI change are used. The Petawawa Research Forest, Ontario, Canada, has red pines (*Pinus resinosa* Ait.) plantations of variable tree densities. For the purpose of understory shade tolerance study, a uniform plantation was divided into two stands. In Stand 1, trees remained intact, while in Stand 2, every other tree in the row was removed, theoretically creating a 50% reduction in the LAI - a perfect case for testing the TRAC theory. TRAC measurements were acquired on September 1, 1998. Six 30 m transects were walked in each of the two stands. The analysis was performed with the revised version of TRACWin[6], the analysis software distributed with the TRAC instrument. Figure 3 shows the $F_m(\lambda,\theta)$ curves for both stands at the solar zenith angle of 38.3° and 39.3° for Stand 1 and 2, respectively. As expected, very large gaps can be found in the Stand 2. The mean gap fraction of the 6 transects in Stand 1 is 0.205 (See Table 1) while Stand 2 has a gap fraction of 0.534. Because the two stands have the same species and age, the woody material and needle-to-shoot ratio corrections[3] are not performed since the goal is to assess the relative change in LAI between the stands. The LAI for Stand 1 is 3.63 with the old method and 3.61 after correction.

	Site 1 (CC)	Site 1 (N)	Site 2 (CC)	Site 2 (N)
Element Width (W_p)	13.0 cm			
Segment length	30 m			
Latitude	46° N			
Longitude	77° 27’ W			
Date of acquisition	1 September 1998			
Time of acquisition	12:35-12:48 (EST)		12:56-13:08 (EST)	
Solar Zenith Angle	38.3°		39.3°	
Gap Fraction	0.205		0.534	
Effective LAI	2.48		0.97	
Clumping Index (Ω_E)	0.94	0.95	0.56	0.70
Leaf Area Index	2.64	2.61	1.73	1.38

Table 1: Information about the two stands and the parameters used to compare the two clumping index retrieval methods, Chen and Cihlar (CC) and the new formulation presented here (N).

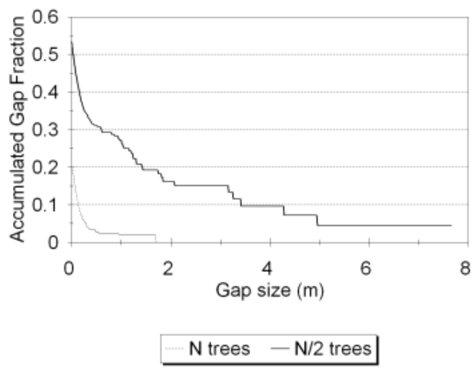

Figure 3: Accumulated gap fraction from two red pine plantations in which the second plantation has half the number of trees than the first plantation.

The old method gave 1.73 for Stand 2 before correction and 1.38 after correction. The difference is sizeable for the open canopy while negligible for the denser one. The LAI ratio between the dense and open canopies is 1.5 with the old method and 1.9 with the new method. The ratio of 1.9 is very close to the expected ratio of 2 given a 50% thinning and indicates that the old derivation of the clumping index was overestimating the LAI.

This test indicates that the original TRAC theory induces a considerable positive bias for very open stands, but the bias is negligible for dense stands.

Conclusion

The derivation of the clumping index from gap size distribution has been corrected and the new formulation shows that the former formulation allowed overestimation of the LAI. A test case of a very open stand showed a decrease in LAI of 20% and resulted in the expected results when comparing two stands where one has twice the LAI than the other.

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