Recent advancements in optical field leaf area index, foliage heterogeneity, and foliage angular distribution measurements.

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***Abstract*-In-situ estimations of leaf area index (LAI), leaf clumping, and leaf angular distribution are often performed from canopy gap fraction measurements with optical sensors. Two new procedures are used in this study to improve the estimation of gap fraction from digital camera photographs,: 1) the Digital Number (DN) of mixed sky-canopy pixels is use to estimate the within pixel gap fraction instead of the usual threshold used to separate a pixel in gap or a foliage pixel, and 2), the within pixel gap fraction is calculated at different view zenith and azimuth angles to take into account multiple scattering effects. To estimate foliage clumping, a gap size distribution is calculated from a narrow view zenith angle range (less than 1°). The clumping index is then extracted using 3 methods: 1) a refined gap size distribution theory developed for the TRAC instruments; 2) The Lang and Xiang logarithm gap fraction averaging and 3) a combination of 1) and 2). Clumping index variations with view zenith angle in the range from 15° to 70° are derived using the individual and combined methods. Analysis of the digital hemispherical photographs shows that 1) the three methods give different clumping estimates, but the angular variation patterns are similar, and 2) canopies with significant angular variation in clumping can induce large errors in the inverted leaf angle distribution when the clumping angular variation is not included in the retrieval. The practical implication of these findings is that LAI, clumping index, and foliage orientation can all be reliably retrieved using digital hemispherical photographs, considerably reducing the number and cost of instruments needed in fieldwork.**

I. Introduction

Leaf area index (LAI) is an important biophysical property of vegetation canopies used in ecological modeling. But LAI is not sufficient to model the canopy interception of solar radiation or precipitation, as its angular and spatial distributions are also required. Very few measurements of canopy gap morphology as a function of zenith angles exist, so species characterization has not yet been possible. Two different approaches have been used to measure the heterogeneity of the foliage. The first method is based on finite-length averaging in which the foliage is assumed to be spatially random [1] and the second is based on the distribution of the gap sizes [2]. Deviation from the random gap size distribution can be used to quantify the amount of foliage clumping in a canopy. This methodology is the basis of the Tracing Radiation and Architecture of Canopies (TRAC) manufactured by 3rd Wave engineering, Ottawa, Ontario. Although the TRAC gives estimates of clumping in a canopy, it does so at the solar zenith angle during measurement. Estimation of the clumping at many zenith angles is challenging because half a day is needed to get a large range of solar zenith angle and the range is limited to the sun's maximum elevation at the plot latitude and date of the measurements [2]. Here we are applying the TRAC theory to digital camera hemispherical photographs taken with a fish-eye lens. The steps into obtaining angular clumping index from hemispherical photographs and the implications on the foliage angular distribution are presented here. Gap fraction and clumping index from hemispherical photographs are compared with TRAC measurements in deciduous and conifer stands.

II. Theory and Methodology

A common methodology used in leaf area index estimation from gap fraction is based on the inversion of Beer's law. When foliage clumping is present, Beer's law can been modified as [3]:

$$P(\theta) = e^{-G(\theta)\Omega(\theta)L_t/\cos(\theta)}, \tag{1}$$

where θ is the zenith angle, $P(\theta)$ is the gap fraction, $G(\theta)$ is the foliage projection coefficient characterizing the foliage angular distribution; L_t is the plant area index (PAI) including leaf and woody materials; and $\Omega(\theta)$ is a parameter determined by the spatial distribution pattern of the foliage elements: the clumping index. If the foliage in the field of view of the instrument is random, then $\Omega(\theta) = 1$. Without the knowledge of $\Omega(\theta)$, the LAI is underestimated due to the presence of large gaps in the canopy. L_t can be found without knowledge of foliage orientation with:

$$L_t = -2\int_0^{\pi/2} \frac{\ln P(\theta)}{\Omega(\theta)} \cos(\theta) \sin\theta d\theta \cdot \tag{2}$$

Alternatively to (2), (1) can be inverted directly at a zenith angle near 57.3° because $G(57.3°)$ is always near 0.5 for foliage angular distribution patterns [4]. To obtain the LAI, the contribution from the woody material needs to be removed and the foliage clumping is needed. Inversion of Beer's law is done on the assumption that foliage is randomly distributed over the extent that the gap fraction is measured. Lang and Xiang [1] proposed a "log" average technique over small segments for which the foliage is assumed to be random. This method is interesting but the choice of the segment length may induce large errors. On the other hand, the gap size distribution does not suffer from the extreme clumping index values sometimes found with the finite-length averaging method. When the foliage is clumped, a canopy will exhibit larger gaps than the gaps predicted under the random assumption. Using a gap removal procedure, large gaps are removed until the accumulated gap fraction curve becomes close to a canopy with a random foliage spatial distribution [2]. The gap fraction of the reduced canopy can then be used to estimate the clumping index as [5]:

$$\Omega(\theta) = \frac{\ln[P(\theta)]}{\ln[P_r(\theta)]} \cdot \frac{[1 - P_r(\theta)]}{[1 - P(\theta)]}, \tag{3}$$

where $P(\theta)$ is the measured gap fraction of a clumped canopy at view zenith angle θ and $P_r(\theta)$ is the reduced gap fraction found from the gap removal procedure. With the knowledge of the clumping index, the foliage projection coefficient can now be more accurately estimated with:

$$G(\theta) = -\ln\left[\overline{P(\theta)}\right] \frac{\cos\theta}{L_t \Omega(\theta)} \,. \tag{4}$$

The angular profile of $G(\theta)$ can be used to estimate the foliage angle distribution. There is an uncertainty in the retrieval due to the fact that L_t is used instead of LAI in the gap size distribution. If the angular variation of the clumping is not considered in (4), the angular variation of $\Omega(\theta)$ is transferred to $G(\theta)$, which can then be wrongly interpretated as foliage orientation effect.

III. Digital Hemispherical Photography

Recent digital cameras with fish-eye lenses have a pixel angular resolution in the same order, or better, that the sun angular disc (0.5°). The measurements in this study were made with the NIKON CoolPix 990 and the FC-E8 fish-eye lens. Frazer et al. [6] reported a small but significant distortion in the NIKON FC-E8 fish-eye used with the CoolPix 950 camera. Assuming the same distortion, not considering it would mean that L_t is underestimated by 4 to 5%.

The photographs taken under canopies are stored in 24-bit colour images, preferably in TIFF format that conserves all Digital Numbers (DN) or high quality JPEG. Tests by Frazer et al. [6] and our own tests indicated that the compression in JPEG resulted in a small effect on the gap fraction retrieval. The images were then saved into red green and blue channels in separate raw 8-bit image files. In-house software was developed to analyse the hemispherical photograph 8-bit raw images. As with the Licor LAI-2000, the blue channel is preferred and was used in almost all images to minimize multiple scattering. In a few rare cases more contrast was found in either the green or red channel. Hemispherical photographs are usually classified into sky and canopy pixels using a threshold value. We used two threshold values for each zenith angle range. They are based on the beginning and ending of the logarithmic part of the histogram (linear part in the "log" plot of Fig. 1a). This worked well for diffuse light, but an adaptive curve for the maximum DN improves the retrieval under sunlit conditions. The low threshold separates complete foliage pixels from mixed sky and foliage pixels. This threshold varies with multiple scattering. The high threshold separates foliage free (gap) pixels from mixed foliage. There is a single threshold that could give an equivalent mean gap fraction, but it is easier and less subjective to find the two thresholds as seen in Figure 1. Assuming a linear response from the CCD array, the percentage of gaps within a pixel is estimated (0 from lower threshold and 1 for highest threshold). The gap fraction is calculated as:

$$P(\theta) = \begin{cases} 0 & \text{if } DN < DN_{Min} \\ \dfrac{DN - DN_{Min}}{DN_{Max} - DN_{Min}} & \text{if } DN_{Min} < DN < DN_{Max} \\ 1 & \text{if } DN > DN_{Max} \end{cases} \,. \tag{5}$$

The within-pixel gap fraction can be used to improve gap size distribution retrieval from hemispherical photography and to get the clumping index. Few studies have used photography to retrieve clumping index [7] [8]. At the resolution of available digital camera these days (e.g. fish-eye circular area with diameter of 1500 pixels), a gap of about 3 to 5 cm at the top of a 15 m canopy is required to get a pixel free of vegetation. This shows the need to get within-pixel gap estimates. This may not be an issue in the near future as digital camera resolution improves. This new threshold method can be used to get gap fraction of annulus rings, or it can be used to estimate sizes of gaps along a narrow annulus ring. An azimuthal DN profile can be extracted (Fig. 1b) and used in the same manner as a PPFD profile for the TRAC instrument [2]. The equivalent to flag markers that are used at a fixed interval length on a transect are replaced by 45° arcs (8 per image). To get representative statistics from 15 to 70° from zenith, four images are usually required. The number of pixels per arc varies with view zenith angle, e.g. 90 pixels at 15° and 433 pixels at 70°. The gap removal was performed with the TRACWin software [9] distributed with TRAC using the number of pixels within a 45° segment as the segment length, which means that the foliage element size is expressed in pixel unit.

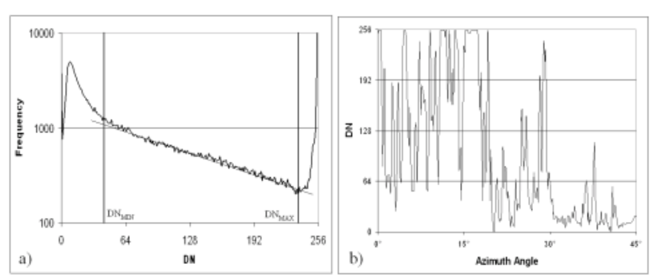

Fig. 1. a) Digital Number (DN) histogram of annulus rings centred at 58° of hemispherical photographs taken in a mixed deciduous conifer stand in Northern-Ontario. b) Extracted azimuthal DN profile of a narrow annulus ring, centred at 58°, used for gap size distribution measurements.

The "log" averaging method was use with the 45° segments, i.e., a value of effective L_t was computed from the gap fraction for each segment assuming the foliage is randomly distributed over the arc. Using 45° arcs reduces the risk of having segments with no gaps that would give an infinite LAI, but the within segment can still have clumped foliage. Using the gap size distribution within each segment, L_t is computed and is used as a third method to estimate the clumping index.

IV. RESULTS-DISCUSSION

Different plots (temperate and boreal forests) were visited with both TRAC and the NIKON CoolPix 990 in the 2001-growing season. At all sites, the TRAC was walked at about 1.5 m from the ground while the hemispherical photographs were taken at 2 m from the ground. One plot is explored in details here: a mixed conifer-deciduous plot in Northern Ontario. The plot is a 70 m transect where flags were put at every 10 m. Fig. 2 shows the retrieved clumping index and foliage projection coefficient $G(\theta)$. In Fig. 2a, it can be seen that the three methods to derive the clumping index follow the same angular pattern. The different clumping index methods are well correlated (R^2 = 0.97), but the gap size distribution method gives clumping index systematically larger than the other two methods. Figure 2b shows that when the clumping is considered, $G(\theta)$ become 0.5 for almost all angles. This indicates that when the clumping angular variation is not considered, the foliage has a strong erectophile behaviour, but in fact, the foliage is most probably randomly oriented. Figure 3 shows a comparison of TRAC measurements and the hemispherical photographs at the view zenith angle equivalent to the solar zenith of TRAC. Different reasons can explain the difference in gap fraction: 1) the camera was held higher than TRAC, seeing less of the canopy and 2) the digital camera suffers from chromatic aberration. The aberration causes some foliage elements to either appear brighter, or to disappear in the blue channel. But the correlation between the TRAC and hemispherical photographs is reasonable considering that they are also not looking at exactly the same part of the canopy.

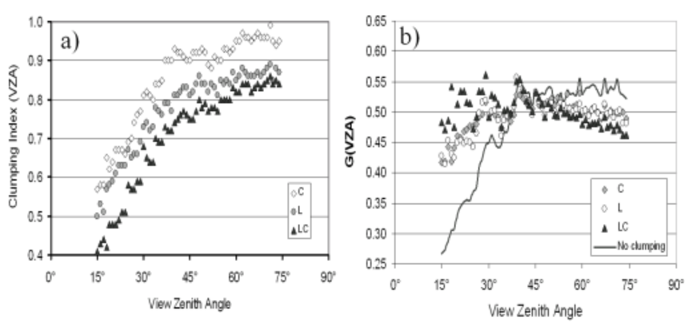

Fig. 2. a) Clumping Index retrieved using different methods from combining seven hemispherical photographs. b) Foliage projection coefficient retrieved using Eq. 4. C is Chen [2] method, L is Lang finite-averaging method [1] and LC is a combination of Chen and Lang methods.

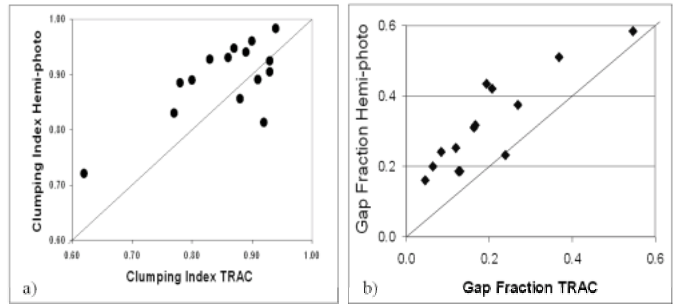

Fig. 3. Comparison of TRAC and hemispherical photography: a) clumping index and b) gap fraction.

TRAC looks in the sun direction while the camera has a 360° view.

V. CONCLUSIONS

A new methodology has been developed to analyze hemispherical photographs for LAI, foliage angular distribution and clumping index estimation. Although the blue channel offers the largest contrast, the chromatic aberration needs to be accounted to measure the proper gap fraction. Nevertheless, the digital camera has a great potential to replace both LAI-2000 and TRAC. Ray tracing of plant canopy will be used to assess the three methods to derive the clumping index presented here.

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