

Tracing Radiation and Architecture of Canopies

TRAC MANUAL Version 2.1.3

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1. Overview

TRAC - Tracing radiation and Architecture of Canopies

The leaf area index (LAI) and the Fraction of Photosynthetically Active radiation (F_{PAR}) absorbed by plant canopies are biophysical parameters required in many ecological and climate models. In spite of their importance, the commercially available techniques for measuring these quantities are often less than adequate. Many studies have relied on commercial instruments such as the LAI-2000 Plant Canopy Analyzer (LI-COR), AccuPAR Ceptometer (Decagon), and Demon (CSIRO) as well as hemispherical photography. However, these optical instruments have been repeatedly found to underestimate LAI of forests and discontinuous canopies where the spatial distribution of foliage elements is not random. TRAC was developed to cope with this problem.

What is TRAC?

TRAC is an optical instrument for measuring the Leaf Area Index (LAI) and the Fraction of Photosynthetically Active Radiation absorbed by plant canopies (F_{PAR}). TRAC measures canopy "gap size" distribution in addition to canopy "gap fraction". Gap fraction is the percentage of gaps in the canopy at a given solar zenith angle. It is usually obtained from radiation transmittance. Gap size is the physical dimension of a gap in the canopy. For the same gap fraction, gap size distributions can be quite different.

Why do we measure gap size?

Plant canopies, especially forests, have distinct architectural elements such as tree crowns, whorls, branches, shoots, etc. Since these structures dictate the spatial distribution of leaves, this distribution cannot be assumed to be random. Previous commercial instruments have been based on the gap fraction principle. Because of foliage clumping in structured canopies, those instruments often considerably underestimate LAI. A canopy gap size distribution contains information of canopy architecture and can be used to quantify the effect of foliage clumping on indirect (i.e., non-destructive) measurements of LAI.

How is the gap size distribution measured?

TRAC (including the recording and data analysis components) is hand-carried by a person (see Figure 1.1) walking at a steady pace (about 0.3 meter per second). Using the solar beam as a probe, TRAC records the transmitted direct light at a high frequency (32 Hz). Figure 1.2 shows an example of such measurements where each spike, large or small, in the time trace represents a gap in the canopy in the sun's direction. These individual spikes are converted into gap size values to obtain a gap size distribution shown in Figure 1.3. The red curve in Figure 1.3 is an accumulated gap fraction, from the largest to the smallest gap. The total accumulated gap fraction on the ordinate (at gap size of zero) is the gap fraction that is usually measured from the radiation transmittance. A gap size distribution curve like this reveals the composition of the gap fraction and contains much more information than the conventional gap fraction measurements.



Figures 1.1 TRAC measures light under the canopy while the operator holds it levelled and walks at a constant slow pace.

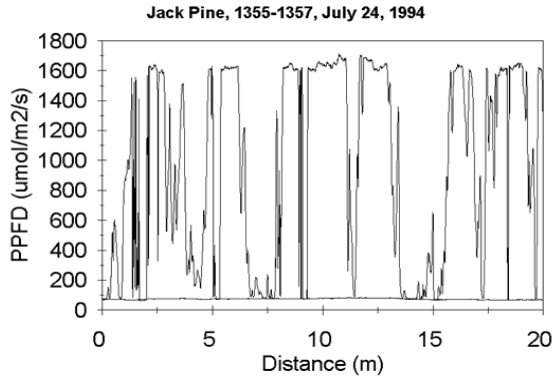


Figure 1.2: An example of TRAC measurements in a mature jack pine stand near Candle Lake, Saskatchewan. The measured photosynthetic photon flux density (PPFD) along a 20 m transect (a small portion of the original 200 m record) shows large flat-topped spikes corresponding to large canopy gaps between tree crowns and small spikes resulting from small gaps within tree crowns. The baseline is the diffuse irradiance under the canopy measured using the shaded sensor.

How is the clumping effect calculated from a gap size distribution?

A gap size distribution contains many gaps that result from non-randomness of the canopy, such as the gaps between tree crowns and branches. Since we know the distribution for a random canopy, F_r in Figure 1.3 (based on Miller and Norman, 1991), the gaps resulting from non-randomness can be identified and excluded from the total gap fraction accumulation using a gap removal method (Chen and Cihlar, 1995a). The difference between the measured gap fraction and the gap fraction after the non-random gaps removal can then be used to quantify the clumping effect.

Has this method been validated?

TRAC technology has been validated in several studies (Chen and Cihlar, 1995a; Chen, 1996a, Chen et al., 1997a; Kucharik *et al.*, 1997; Leblanc 2002). These studies showed that instruments based on gap fraction, such as LI-COR LAI-2000, measure the effective LAI, under the assumption of random leaf spatial distribution. In forest stand, only the effective Plant Area Index (PAI) can be measured directly because optical instruments cannot differentiate between woody material and leaves. Effective PAI is generally only 50% to 80% of the true PAI because of clumping. The clumping index obtained from TRAC can be used to convert effective PAI to PAI. Leblanc (2002) showed that the TRAC can accurately measure a change in PAI when trees are cut, inducing clumping in a canopy. When TRAC is used for half a clear day, or at solar zenith angle near 57.3° , an accurate LAI value for a stand can also be obtained using TRAC alone.

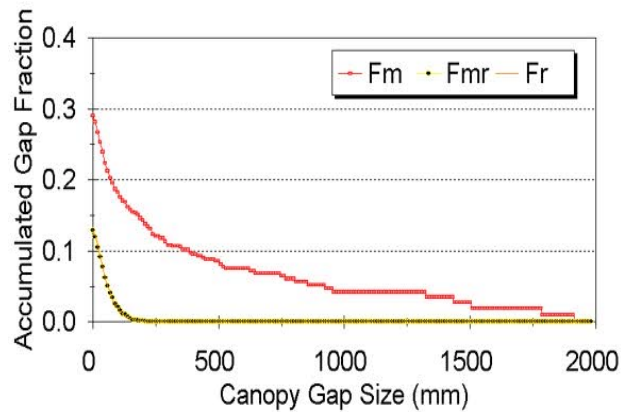


Figure 1.3: The original measurements shown in Fig. 1.2 are converted into this canopy gap accumulation curve (F_m) where the gap fraction is accumulated from the largest gap (about 1.8 m in this case) to the smallest gap. The accumulated gap fraction at canopy gap size of zero is the total canopy gap fraction as measured from the total radiation transmittance. After using a gap removal approach, the measured gap size distribution (F_m) becomes (F_{mr}) and is brought to the closest agreement with the distribution (F_r) predicted by the random theory (Miller and Norman, 1971). In this case F_{mr} and F_r agree very closely. The difference between F_m and F_{mr} on the ordinate determines the clumping index while F_m determines the “effective PAI”.

It is recommended (Chen et al., 1997a) that TRAC be used to investigate the foliage spatial distribution pattern while hemispherical viewing instruments such as the LAI-2000 be used to study foliage angular distribution pattern. The combined use of TRAC and LAI-2000 allows quick and accurate LAI assessment of a canopy.

2. The TRAC Instrument

TRAC has three modes: standby, data logging and data transfer. TRAC switches between the standby mode and the data-logging mode whenever the control button is held down for 1/2 second or more. A mode change is indicated by a beep signal. In standby mode, TRAC clicks once per second. In data logging mode, TRAC clicks 32 times per second. **The 512K bytes of memory holds 45 minutes of data collected at 32 readings per sensor per second. Wrap around occurs after this capability is exceeded, i.e., the newest data will overwrite the oldest.**

TRAC serially outputs sensor reading in $\mu\text{mol s}^{-1} \text{m}^2$ units, in ASCII. A set of readings from the three sensors is arranged as "1111 3333 2222" where 1111 is a reading from sensor 1, etc. The valid output range is 0000 to 4095. The distance markers are formatted during transfer as: "9999 mm-dd-yyy hh:mm:ss"



Figure 2.1: TRAC consists of 3 PAR sensors (400 to 700 nm) and amplifiers, an analog-to-digital converter, a microprocessor, a battery backed memory, a clock and serial I/O circuitry. A power switch controls the power to all components of the system except the memory. A control button controls the operating mode when the power is on. This button is also used to insert distance/time markers.

Battery Replacement

Erratic behaviour of the instrument is usually due to near exhaustion of the 9-volt battery, which provides about 40 hours of operation. It is highly recommended to have fresh batteries at hand at all time. To replace the batteries (see Fig. 2.2), open the left-cover of the instrument by removing the four screws. The 3-volt lithium cell should be replaced once a year. **Note that TRAC will acquire data even if the 3-volt battery failed, but the data will not be recorded.**

General Care and Maintenance

TRAC is designed to be rugged and reliable. Apart from battery changes, TRAC is practically maintenance free. For prolonged, trouble-free service, please observe the following "common sense" recommendations:

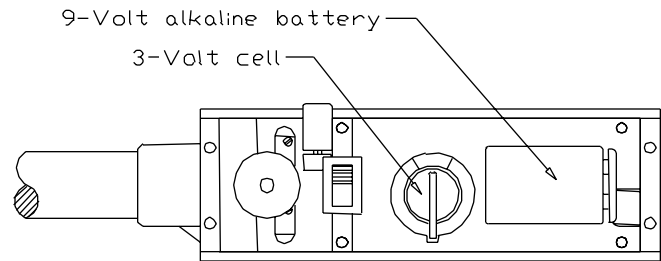


Figure 2.2: Batteries inside TRAC

Calibration potentiometers: The three potentiometers under the cover have been adjusted to match the characteristic output of the three sensors. **User adjustment is not recommended.**

Do not remove the sensor serial number stickers.

Cleaning: clean the LI-COR sensors and plastic part with only water and/or a mild detergent such as dish washing soap.

Avoid high temperature: Prolonged exposure to high temperature may distort plastic parts. Do not leave the instrument in direct sun in parked vehicle. The carrying case will compound the problem in this situation.

Protect from rain: The sensors are water-resistant but the instrument housing is not. Wetness will not permanently damage the instrument but may cause erratic operation.

Protect from sand: Sand may cause the control button to jam. Use the dummy plug provided to protect the serial connector from sand and dirt.

3. TRAC THEORY

3.1 Leaf Area Index (LAI)

The LAI is defined as one half of the total leaf area per unit ground surface (Chen and Black, 1992a). The major advantage of this definition over the definition based on the projected (one-sided) area (Ross 1981) is that when the foliage angular distribution is random, the usual projection coefficient of 0.5 can still be used for object of any shape. Since foliage elements are oriented in various directions in plant canopies, the projected area in one direction does not contain all the information for estimating radiation interception. The use of half the total area, which in effect is twice the average projected area for all leaf inclination angles, avoids this problem.

Many optical instruments measure canopy gap fraction based on radiation transmission through the canopy. The substantial difference between the LAI measured with these

instruments and TRAC is perhaps better understood with the following expression (based on Nilson, 1971):

$$P(\theta) = e^{-G(\theta)\Omega(\theta)L_t / \cos(\theta)} \quad (3.1)$$

where $P(\theta)$ is the gap fraction, $G(\theta)$ is the foliage projection coefficient characterizing the foliage angular distribution (see Warren Wilson and Reeve, 1959, or Norman and Campbell, 1989, for expressions of $G(\theta)$ with foliage orientation); L_t is the plant area index (PAI) including leaf and woody material; and $\Omega(\theta)$ is a parameter determined by the spatial distribution pattern of the foliage elements. When the foliage spatial distribution is random, $\Omega(\theta)$ is unity. If leaves are regularly distributed (extreme case: leaves are all laid side by side), $\Omega(\theta)$ is larger than unity. When leaves are clumped (extreme case: leaves are stacked on top of each other), $\Omega(\theta)$ is less than unity. Foliage in plant canopies are generally clumped, hence $\Omega(\theta)$ is often referred as the clumping index. Miller (1967) simplified the inversion of Eq. (3.1) by showing that

$$\int_0^{\pi/2} G(\theta) \sin \theta d\theta = 0.5 \quad (3.2)$$

for any foliage orientation probability. Isolating $G(\theta)L_t$ in Eqs. (3.1) and integrating using the relation from (3.2) yields (Fernandes *et al.*, 2001):

$$L_t = 2 \int_0^{\pi/2} -\frac{\ln[P(\theta)]}{\Omega(\theta)} \cos \theta \sin \theta d\theta \quad (3.3)$$

Equation 3.3 implies that the gap fraction and clumping index have to be measured from 0 to 90 degrees. Some approximations can and have been used to simplify this problem. If $\Omega(\theta)$ can be assumed constant with θ , then Eq. (3.3) becomes:

$$L_{et} = L_t \cdot \Omega = -2 \int_0^{\pi/2} \ln P(\theta) \cos(\theta) \sin \theta d\theta \quad (3.4)$$

The product of L_t and Ω is called the effective PAI (L_{et}). On the other hand, if the variation of $\Omega(\theta)$ is important but the variation of $G(\theta)$ is small, which is the case when the foliage is close to be randomly distributed and $G(\theta)$ can be fixed at 0.5, using 3.1 and 3.2 gives:

$$L_t = -2 \frac{\int_0^{\pi/2} \ln[P(\theta)] \cos \theta \sin \theta d\theta}{\int_0^{\pi/2} \Omega(\theta) \sin \theta d\theta} \quad (3.5)$$

In that case, the integral on the denominator $\int_0^{\pi/2} \Omega(\theta) \sin \theta d\theta = \Omega$ and again we have $L_{et} = \Omega L_t$.

Another approach to simplify Eq. (3.3) is based on Lang (1987). First, we assume that $\Omega(\theta) = 1$ and we replace $-\ln P(\theta) \cos(\theta)$ by a polynomial function, then the integration of the polynomial can be solved analytically. Tests have shown that to get all different forms of $-\ln P(\theta) \cos(\theta)$, a polynomial of order 5 is high enough: $A + B\theta + C\theta^2 + D\theta^3 + E\theta^4 + F\theta^5$. Obviously, good fits are possible with lower order than 5. Let's first look at the case where $-\ln P(\theta) \cos(\theta) = A + B\theta$. A simple regression can tell if the canopy study can be approximated this way. This method is suggested in the LAI-2000 manual as an alternative to get LAI. This implies that

$$\begin{aligned} L_{et} &= -2 \int_0^{\pi/2} \ln P(\theta) \cos(\theta) \sin \theta d\theta \\ &= 2 \int_0^{\pi/2} (C\theta + D) \sin \theta d\theta = 2(C + D) \end{aligned} \quad (3.6)$$

The curve $C\theta + D$ is equal to $C + D$ at $\theta_E = 1$ radian, which is 57.3° . We denote θ_E the equivalent angle at which L_{et} is the same as to Miller's equation. For any order, there is always an angle that has the same solution as the integral. For order 2, the angle that will give the same L_{et} as Miller's theorem is

$$\theta_E = \frac{C \pm \sqrt{C^2 - 4B^2(\pi - 2) + 4BC}}{2B} \quad (3.7)$$

With higher order polynom, the angle is more complex to determine but is generally in the $50-70^\circ$ range with frequent occurrence at 57.3° . This yields

$$\begin{aligned} & - \int_0^{\pi/2} \ln P(\theta) \cos(\theta) \sin \theta d\theta \\ &= -\ln P(\theta_E) \cos(\theta_E) = G(\theta_E) \cdot L_t \cdot \Omega(\theta_E) \end{aligned} \quad (3.8)$$

Measurements also show that this occurs usually at the angle where $G(\theta_E)$ is 0.5 (Figure 3.1). So the total plant area index can be computed either with Eq. (3.3), with

$$L_t = -\frac{2}{\Omega(\theta_E)} \int_0^{\pi/2} \ln P(\theta) \cos \theta \sin \theta d\theta, \quad (3.9)$$

or with

$$L_t = -\frac{2}{\Omega(\theta_E)} \ln P(\theta_E) \cos(\theta_E) \quad (3.10)$$

The angle may not always be exactly 57.3° for Eq. (3.9), but the gap fraction from many angles can be used to verify this by comparing the integral to the value at that angle. Eq. (3.9) is similar to the methodology used by Chen *et al.*, (1997a) where clumping from a single zenith angle was used to correct the effective plant area index measured with the LAI-2000. The only difference is that the clumping index from 57.3° is preferred.

Conifer needles are grouped at several levels: shoots, branches, whirls and tree crowns, and even groups of trees. Conifer shoots (the basic collection of needles distributed around the smallest stem) are treated as the basic foliage units affecting radiation transmission (Norman and Jarvis, 1975; Ross *et al.*, 1986; Oker-Blom, 1986; Leverenz and Hinkley, 1990; Gower and Norman, 1990; Fassnacht *et al.*, 1994). Chen and Black (1992b) and Chen and Cihlar (1995a) determined from canopy gap size distributions that the size of the basic foliage unit is the average projected shoot width. This is because small gaps disappear in the shadow in a short distance as a result of the penumbra effect.

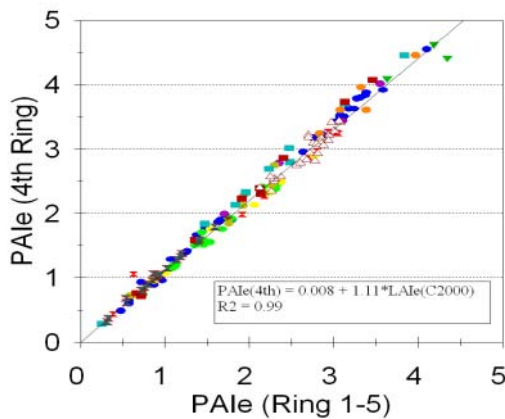


Figure 3.1: Comparison between LAI-2000 effective PAI (PAIe) retrieved using 5 annulus rings and from only one annulus ring (47-58°). The fit is almost perfect ($R^2=0.99$) with a systematic increase due to multiple scattering in the fifth ring (See Leblanc and Chen, 2001) and the presence of clumping that varies with zenith angle. The measurements are from different species in Ontario and Quebec (see Chen *et al.*, 2002).

Therefore it is difficult to measure the amount of needle area within the shoots with optical instruments and the $\Omega(\theta)$ value has to be separated into two components as follows (Chen, 1996a):

$$\Omega(\theta) = \frac{\Omega_E(\theta)}{\gamma_E}, \quad (3.11)$$

where γ_E is the needle-to-shoot area ratio quantifying the effect of foliage clumping within a shoot (it increases with increasing clumping) and $\Omega_E(\theta)$ includes the effect of foliage clumping at scales larger than the shoot (it decreases with increasing clumping).

The needle-to-shoot area ratio is used to quantify foliage clumping within shoots. Fassnacht *et al.* (1994) proposed an equation for calculating the shoot area, which is an improvement over the method of Gower and Norman (1990). Chen (1996a) developed the following equation to calculate one half of the total shoot area (A_s), which differs slightly from Fassnacht *et al.* (1994):

$$A_s = \frac{1}{\pi} \int_0^{2\pi} d\Phi \int_0^{\pi/2} A_p(\theta, \Phi) \cos \theta d\theta, \quad (3.12)$$

where θ is the zenith angle of projection relative to the shoot main axis, and Φ is the azimuthal angle difference between the projection and the shoot main axis. A shoot having an equal projected area at all angles of projection can be approximated by a sphere. In such a case A_s , half the total shoot imaginary surface area, equals 2 times the projected area. If one half of the total area (all sides) of needles in a shoot is A_n , then

$$\gamma_E = A_n / A_s \quad (3.13)$$

For deciduous forests, individual leaves are considered as the foliage elements and $\gamma_E=1$.

Kucharik *et al.* (1999) explored the importance of the angular variation of $\Omega_E(\theta)$. They proposed the following equation to get the clumping index at different θ :

$$\Omega_E(\theta) = \frac{\Omega_{E,MAX}}{1 + b \exp(-k\theta^p)}, \quad (3.14)$$

where p and k are constants, θ is the zenith angle (in radian), and b can be found by solving (3.14) with one measurements of $\Omega_E(\theta)$ and

$$\Omega_{E,MAX} = \left(\frac{ND}{\sqrt{B}} \right)^{0.7}, \quad (3.15)$$

where N is the number of stems in a area B and D is the crown diameter. The constants are species dependent. Kucharik *et al.* (1999) found through Monte Carlo simulations the following: aspen: $p = 3.0$ and $k = 1.6$, and for conifers like jack pine and black spruce: $p = 1.72$ and $k = 2.38$. Figure 3.2 is a reproduction of TRAC measurements made during BOREAS (Chen 1996a). Fig. 3.2 shows that the variation of the measured $\Omega_E(\theta)$ do not always have the behaviour of Eq. (3.14).

The data is often well approximated by a linear curve (see also Leblanc *et al.*, 2001b) for the 30-70° range. Moreover, Fig. 3.3 shows simulations done with the Five-Scale model (Leblanc and Chen, 2000). The Five-Scale curves include clumping at all scales while Fig. 3.2 includes only the clumping at the scale larger than the shoots. The shape of the Five-Scale curves is more closely related to the data than Kucharik *et al.* (1999) curves.

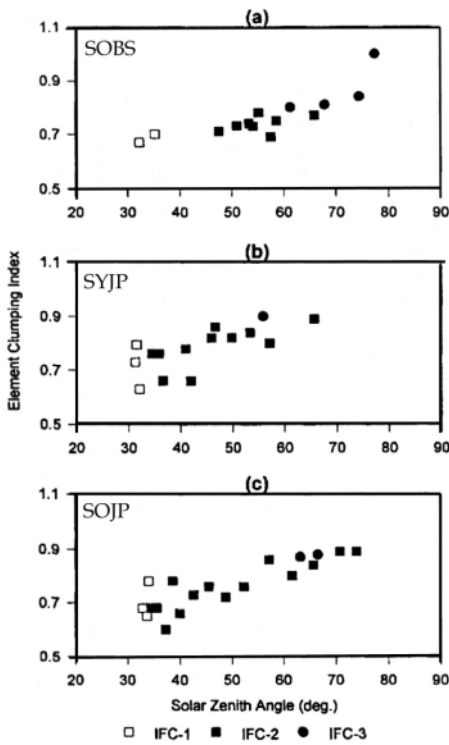


Figure 3.2: Change of element clumping index with solar zenith angle measured with TRAC (Chen 1996a) for a) the southern BOREAS old black spruce, b) the southern BOREAS young jack pine, and c) the southern BOREAS old jack pine sites. Note that this figure was done using the old clumping index derivation and it is now expected to exhibit a lesser angular variation for the solar zenith angle range showed.

An approximation of the Five-Scale curves can be obtained with a polynomial of degree three: $\Omega(\theta) = A + B\theta + C\theta^2 + D\theta^3$.

As stated by Kucharik *et al.* (1999), $\Omega(\theta=90^\circ)$ tends to go to unity since both clumped and random based gap fraction will go to zero, but since the value is not used in the calculation with Miller's equation ($\sin(90^\circ)=0$), it is better not to use that point in a regression to find A, B, C and D.

Since L_t is obtained from gap fraction measurements, and is the quantity that many optical instruments measure, Chen (1996a) used it as a basis for calculating LAI using the following equation:

$$L = L_t(1 - \alpha) \quad (3.16)$$

where α is the woody-to-total area ratio. Since L_t is usually measured near the ground surface based on radiation transmission, all above-ground materials, including green and dead leaves, branches, and tree trunks and their attachments (lichen, moss), intercept light and are included in L_t . By using the factor $(1-\alpha)$, the contributions of non-leafy materials are removed.

However, the removal using this simple parameter assumes a non-woody material has a spatial distribution pattern similar to that of leaves quantified by $\Omega(\theta)$ and that it is independent of the zenith angle.

This assumption may result in a small error in the LAI estimation. The value of α is obtained through destructive sampling (Chen, 1996a) or from measurements taken before leaf emergence or after leaf-off (Chen *et al.*, 1997b; Leblanc and Chen, 2002).

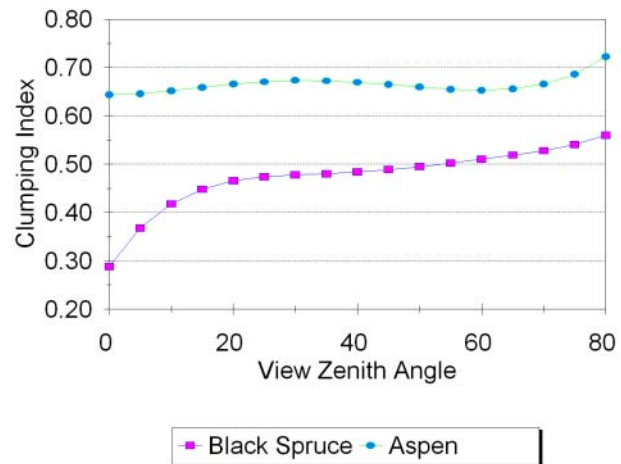


Figure 3.3: Five-Scale Simulations of the clumping index versus the view zenith angle for two boreal forests (from Leblanc and Chen, 2002).

New ways of estimating α have been investigated using a two-band camera (Kucharik et al., 1997). The remaining task in obtaining LAI is to determine $\Omega(\theta)$.

3.2 TRAC measurements of LAI and foliage clumping index

If foliage elements, i.e., leaves of deciduous canopies and shoots of conifer canopies, are randomly distributed in space, $\Omega(\theta)$ equals unity and only γ_E and α are needed for calculating LAI of conifer canopies from gap fraction estimates. For most plant canopies, foliage elements are clumped, resulting in $\Omega(\theta)$ smaller than unity. When foliage elements are grouped at higher levels, the total gap fraction increases for the same LAI, and so does the probability of observing large gaps. A canopy gap size distribution can therefore be used to quantify $\Omega(\theta)$. The TRAC is designed to acquire the gap size distribution through measurements of sunfleck widths along transects beneath the canopy. The corrected equation for calculating $\Omega_E(\theta)$ is (Leblanc 2002)

$$\Omega_E(\theta) = \frac{\ln[F_m(0)]}{\ln[F_{mr}(0)]} \cdot \left[1 + \frac{F_m(0) - F_{mr}(0)}{[1 - F_m(0)]} \right] \quad (3.17)$$

where $F_m(0)$ is the measured total canopy gap fraction, and $F_{mr}(0)$ is the gap fraction for a canopy with randomly positioned elements. While $F_m(0)$ can be measured as the transmittance of direct or diffuse radiation at the zenith angle of interest, $F_{mr}(0)$ is obtained through processing a canopy gap size accumulation curve, $F_m(\lambda)$, which is the accumulated gap fraction resulting from gaps with size l larger than or equal to λ . At $\lambda = 0$, $F_m(\lambda)$ is the total gap fraction as measured by other optical instruments. $F_m(\lambda)$ can be measured by the TRAC. According to Miller and Norman (1971), the pattern of gap size accumulation for a random canopy, denoted by $F_r(\lambda)$, can be predicted from LAI and the foliage element width. By comparing $F_m(\lambda)$ with $F_r(\lambda)$, large gaps appearing at probabilities larger than the prediction of $F_r(\lambda)$ can be identified and removed from the total gap accumulation. $F_{mr}(\lambda)$ is $F_m(\lambda)$ brought to the closest agreement with $F_r(\lambda)$, representing the case of a random canopy with the same LAI. In the calculation of $F_r(\lambda)$, LAI is required, but it is unknown. Chen and Cihlar (1995a) solved the problem by using an iteration method. For a given measured $F_m(\lambda)$, the iteration always converges to a unique value.

In general, for n measurements at zenith angle θ_i , $i = 1, \dots, n$, the $\sin \theta$ weighting scheme can be used, i.e.

$$L_t = - \frac{2 \sum_{i=1}^n \frac{\ln(P(\theta_i)) \cos(\theta_i) \sin(\theta_i) \Delta\theta_i}{\Omega(\theta_i)}}{\sum_{i=1}^n \sin(\theta_i) \Delta\theta_i} \quad (3.18)$$

where $\Delta\theta_i$ is the angular range over which $P(\theta_i)$ is measured. In using Eq. (3.18), it is suggested that TRAC measurements be made at a regular θ_i interval within the angle range from 0° to 60° . This is a difficult task since the TRAC transect needs to be perpendicular to the sun, which means the transect may need to be moved for different time of the day. Eq. (3.16) can be used to get L_t from multiple angular gap fraction measurements from other instruments. Eq. (3.18) is the discrete approximation of Eq. (3.3) if the summation is done over the range 0 to 90° , eliminating the need for the assumption of random distributed foliage. An alternative is to get the effective LAI from the angle θ_E (from Eq. 3.9):

$$L_t = - \frac{2 \sum_{i=1}^n \ln(P(\theta_i)) \cos(\theta_i) \sin(\theta_i) \Delta\theta_i}{\Omega(\theta_E) \sum_{i=1}^n \sin(\theta_i) \Delta\theta_i} \quad (3.19)$$

or more simply, the summation is done from only the gap fraction at θ_E . The clumping at θ_E can be measured exactly by TRAC or extrapolated from other zenith angles. In general, if the clumping index is measured at a smaller zenith angle, the clumping index at θ_E will be larger. The reasons for using a θ_E 57.3° can be seen in Leblanc and Chen (2001) that showed that PAI_e near in the range 48 - 58° is always close to PAI_e from Miller's theorem (see Fig. 3.1). This has been known for a long time (Warren Wilson, 1960; Neumann et al., 1989) but not often used in LAI retrieval.

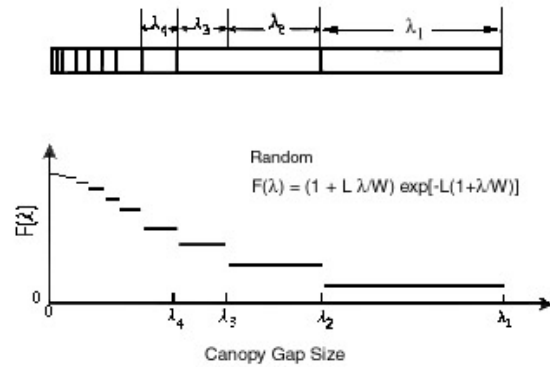


Figure 3.4 Schematic canopy gap size distribution measure on a transect beneath the canopy, where $F(\lambda)$ is the fraction of the transect that is occupied by gaps larger than λ .

3.3 Details of TRAC Theory

The theory presented here follows Chen and Cihlar (1995a) and the modification by Leblanc (2002).

Sunflecks on the surface 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. If a canopy is homogeneous at large scales, sunfleck measurements on a transect in any direction more than 10 times longer than the average tree spacing can statistically represent the canopy with an accuracy of 95% according to the Poisson probability theory. Otherwise, they 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 (Figure 3.4), where $F(\lambda)$ denotes the fraction of the transect occupied by gaps (sunflecks) larger than λ . In Figure 3.4, $F(\lambda) = 0$ 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 , $F(\lambda)$ in Figure 3.3 would appear to be a horizontal line from 0 to λ_1 at a value of λ_1/L . 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.

3.4 Random Canopy

The theory in this section assumes a canopy with negligible woody material. Miller and Norman (1971) showed that for a canopy with horizontal leaves randomly distributed in space and the sun at zenith, $F(\lambda)$ is determined as follows:

$$F(\lambda) = (1 + \rho w \lambda) e^{-\rho(\sigma + w \lambda)} \quad (3.20)$$

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 (1992b), Eq. (3.20) can be rewritten as

$$F(\lambda) = \left(1 + L \frac{\lambda}{W}\right) e^{-L(1 + \lambda/W)}, \quad (3.21)$$

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

$$W = \frac{\sigma}{w}. \quad (3.21)$$

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

$$W = c w, \quad (3.22)$$

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

For conifer stands, shoots are identified as the basic foliage units or elements (please refer to Results). To apply Eq. (3.21) to plant canopies with the sun at a non-zero zenith angle and non-horizontal foliage elements, several modifications need to be made. First, L is to be replaced by L_p (projected L_E) defined as

$$L_p = \frac{G(\theta) L_E}{\cos \theta}, \quad (3.23)$$

where $G(\theta)$ is the projection coefficient determined by the incident angle θ and the distribution of the foliage element normal, 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 leaf area index L ; but if shoots are identified as elements, L_E becomes the shoot area index (assuming $L_E = L/\gamma$).

The second modification to Eq. (3.21) 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

$$W_p = \frac{\bar{W}}{\cos \theta_p} \quad (3.24)$$

where \bar{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 this equation 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:

$$\cos \theta_p = \sqrt{\frac{\cos^2 \theta + \tan^2 \Delta \beta}{1 + \tan^2 \Delta \beta}} \quad (3.25)$$

where $\Delta\beta$ is the difference in the azimuthal angles of the sun and the transect. In this equation, θ_p varies from 0, at $\Delta\beta = \pi/2$, to θ , at $\Delta\beta = 0$ or π . After these modifications, Eq. (3.21) becomes

$$F(\lambda) = \left[1 + L_p \frac{\lambda}{W_p} \right] e^{-L_p(1+\lambda/W_p)} \quad (3.26)$$

3.5 Non-random Canopies

The spatial distribution of foliage elements (e.g. shoots) is seldom random, and therefore any measured distribution (denoted $F_m(\lambda)$) 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 are generally clumped, resulting in larger canopy gap fractions than those of random canopies with the same LAI. When a canopy is clumped, not only the gap fraction increases 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 $\Omega_E(\theta)$ is given in the following equation (similar to Eq. 3.1):

$$P(\theta) = e^{-G(\theta)\Omega_E(\theta)L_E / \cos \theta} \quad (3.27)$$

where $P(\theta)$ is the probability of a solar beam at an incidence angle θ penetrating the canopy without being intercepted. This equation demonstrates that canopy gap fraction measurements by the LAI-2000 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

$$\Omega_E(\theta)L_E = -\frac{\cos \theta}{G(\theta)} \ln[F_m(0)] \quad (3.28)$$

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

$$L_E = -\frac{\cos \theta}{G(\theta)} \ln[F(0)] \quad (3.29)$$

where $F(0)$ is $F(\lambda)$ at $\lambda = 0$. Combining Eqs. (3.28) and (3.29) results in

$$\Omega_E(\theta) = \frac{\ln[F_m(0)]}{\ln[F(0)]} \quad (3.30)$$

This equation 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 will be 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. 3.26), which requires input of the element size W_p and the projected element area index L_p defined in Eq. (3.23). 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 Norman (1990) and Fassnacht *et al.*, (1994) made corrections to the LAI-2000 measurements based on the assumption that shoots of conifers are the basic foliage units responsible for radiation interception. From sunfleck size distributions in a Douglas-fir stand, Chen and Black (1992) derived an element size, which 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. Section 3.7 shows how TRACWin derived the foliage element size based on Chen and Black's method. To determine L_p , it is required to know L_E (Eq. 3.23), 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.

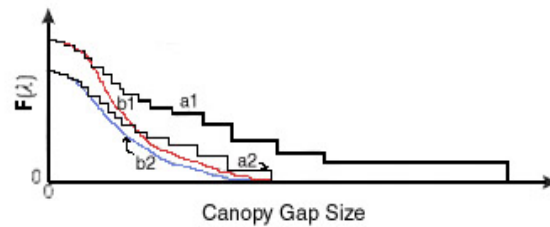


Figure 3.5: Gap-size distributions and re-distributions after two gap removal processes where a1 is a measured gap-size distribution, b1 is the first estimate of the distribution for a random canopy, a2 is the redistribution after the two largest gaps are removed, b2 is the second estimate. In finding the final distribution for the calculation of the clumping index. The process is repeated until the distribution is brought to the closest agreement with the distribution for a random canopy.

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. 3.23 and 3.26, 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. the new distribution $F_{mr}(\lambda)$ becomes closely overlapped with $F(\lambda)$.

Fig. 3.5 demonstrates the changes in $F_{mr}(\lambda)$ with the iterations. Curve a1 is the measured distribution $F_m(\lambda)$ and curve b1 is a predicted distribution $F_r(\lambda)$ for the case of random foliage distribution using measured W_p and the first estimate of L_p . The non-randomness of the canopy is seen from the difference in curves a1 and b1: many large gaps appear at probabilities much larger than $F_r(\lambda)$. After some of the excessive gaps are removed, the first estimate of $F_{mr}(\lambda)$ is formed as curve a2 and the second $F_r(\lambda)$, curve b2, is obtained using the same W_p but different L_p obtained from $F_{mr}(\lambda)$, ensuring $F_r(0) = F_{mr}(0)$. 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_t . 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 non-zero probability for the appearance of a gap of however large size, a small portion of a truncated gap remains. Many such partial truncations makes $F_{mr}(\lambda)$ smoother after each iteration. The iteration stops when either the increase in L_p becomes very small or a portion of $F_{mr}(\lambda)$ falls below $F_r(\lambda)$. The later case happens more often because measured distributions at small λ values always deviate to some extent from the ideal random conditions.

Fig. 3.6 illustrates the rationale for the gap removal approach. Assuming 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 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. 3.6 is not a realistic case. However, the gap size analysis method presented above does NOT require the assumption of the local randomness because only the gaps resulting from foliage clumping are removed and the gaps appearing at probabilities in accord with $F_r(\lambda)$ are kept. In other words, in the gap removal process, the foliage elements are computationally rearranged in space to form a random canopy.

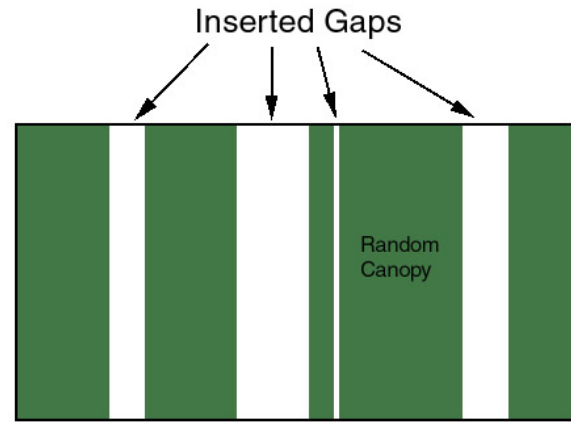


Figure 3.6. Gap removal approach to reconstructing a random canopy for LAI calculations. Large gaps between foliage clumps (crowns, branches, etc) are considered to be “inserted” non-random gaps.

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 (Leblanc 2002)

$$\Delta g = \frac{F_m(0) - F_{mr}(0)}{1 - F_m(0)} \quad (3.31)$$

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

$$L_{Ec} = -\frac{\cos\theta}{G(\theta)} \ln[F_{mr}(0)]. \quad (3.32)$$

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

$$L_E = -\frac{\cos\theta}{(1 + \Delta g)G(\theta)} \ln[F_{mr}(0)]. \quad (3.33)$$

From Eqs. (3.28) and (3.33), it can be shown that

$$\Omega_E(\theta) = \frac{\ln[F_m(0)]}{\ln[F_{mr}(0)]} (1 + \Delta g) \quad (3.34)$$

After the gaps removal, $F_{mr}(0)$ equals $F_r(0)$. $F_r(0)$ differs from $F(0)$ because of the canopy compaction is not considered in $F(0)$. Eq. (3.34) is a slight modification to Eq. (3.30) to consider the compactness of the canopy involved in the gap removal. 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 $\Omega_E(\theta)$ values lies largely in determining $F_{mr}(0)$ from a measured gap size distribution.

3.6 FPAR Theory

FPAR is defined as the fraction of incident PAR that is absorbed by the canopy. The canopy is usually defined as the overstory of the forest stand. By this definition, FPAR excludes the fraction of PAR reflected by the canopy and the fraction absorbed by the underlying surface including the soil, ground cover and understory but includes the small fraction of PAR that is absorbed by the canopy after the reflection by the underlying surface. To obtain FPAR, it is therefore required to measure the downwelling and upwelling PAR at two levels: immediately above and below the canopy. When such measurements at time t are available, the instantaneous FPAR, denoted by $F(t)$, is then calculated as follows:

$$F(t) = \frac{(P_{d1} - P_{u1}) - (P_{d2} - P_{u2})}{P_{d1}} \quad (3.35)$$

where P_{d1} and P_{u1} are the downwelling (incident) and upwelling (reflected) PAR at level 1 (above the canopy), respectively; P_{d2} and P_{u2} are the corresponding terms at level 2 (below the canopy). In this equation, the fraction of PAR that is absorbed by the canopy after reflection by the underlying surface is also considered. After taking the ratio of the downwelling and upwelling irradiance at the same level, Eq. (3.35) can be rewritten as:

$$F(t) = (1 - \rho_1(t)) - (1 - \rho_2(t)) \frac{P_{d2}}{P_{d1}} \quad (3.36)$$

where $\rho_1(t)$ and $\rho_2(t)$ are, respectively, the PAR reflectivity above and below the canopy. Since the reflectivities are small and generally do not vary much between different types of stands, Eq. (3.36) demonstrates that the major task in measuring F_{PAR} is to obtain P_{d2} and P_{d1} simultaneously. While the above stand P_{d1} does not vary spatially under clear conditions and can be measured with a stationary sensor or predicted when data are missing, the below canopy P_{d2} is highly variable in space and time and much more effort is needed to obtain the spatially averaged values. TRAC has three PAR sensors; from the spatial distribution of PAR measured by TRAC underneath the canopy, the mean value of P_{d2} can be calculated. The upward- and downward-facing PAR sensors of TRAC provide accurate measurements of ρ_2 while the reflectivity above the stand can be measured on tower or estimated. ρ_1 of vegetated canopies is usually smaller than 5%.

3.7 Gap Size distribution model (The “P” approach)

The P approach (see Chen and Cihlar, 1995b) is described here only to show how the element size can be computed from the TRAC measurements.

The following formula describes the gap size distribution of a canopy with random spatial distribution of foliage elements:

$$P(\lambda) = e^{-L_p(1+\lambda/W_p)} \quad (3.37)$$

When plotting $\ln(P[\lambda])$, the intercept is $-L_p$ and the slope at zero is L_p/W_p (see Figure 3.7). Which can be used to calculate W_p . W_p estimated from the TRAC measurements is usually larger than from foliage sampling. The *PFL file has the slope at each λ .

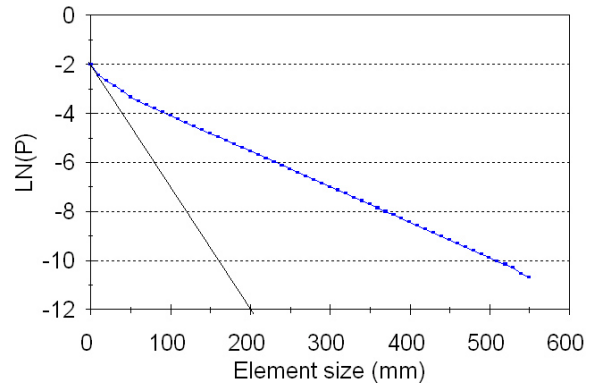


Figure 3.7: In this plot, $L_p = 1.996$ and the slope at 0 is -0.04434 which gives a W_p of 45 mm. The typical width (W) for that forest was about 35 mm based on sampled leaves. The random part of the curve (constant slope) has an element width of 183 mm. See Chen and Cihlar (1995b) for more details. If the operator walks too fast, small gaps won't be visible and W_p computed may be larger than the actual foliage typical width.

4. FIELD MEASUREMENTS

4.1. The Transect

Transect length: In order to characterize the architecture of a canopy, the transmitted direct solar beam needs to be samples over a long transect. Theoretically, the length of the transect should be at least 10 times the average distance between the major foliage structures such as crowns and crop rows. In forest stands, trees are usually found in clusters, so the transect needs to be substantially larger than a few tens of meters to consider the patchiness of the stands. Transects of 100-300 m are recommended. However, it is emphasised that the principle of the clumping and LAI calculation is not compromised by the transect length. TRAC can be used for any transect length, and the LAI values obtained just represent the transect measured in a stand which can be highly inhomogeneous at both small and large scales. Do not forget that TRAC is not measuring gaps above (zenith) the transect, but in the sun's direction. *For cases where very little light is reaching the sensor on a transect, it is suggested that a reference measurement be taken in an opening just before or after the transect measurements.*

Transect and plot size: If the TRAC measurements are going to be used jointly with other measurements (e.g., DBH, LAI-2000) you need to be aware of the TRAC "footprint". Figure 4.1 shows a plot (green background) and trees that can influence the TRAC if it is walked near the edge. Figure 4.2 shows an example of the actual contact points that are measured by TRAC.

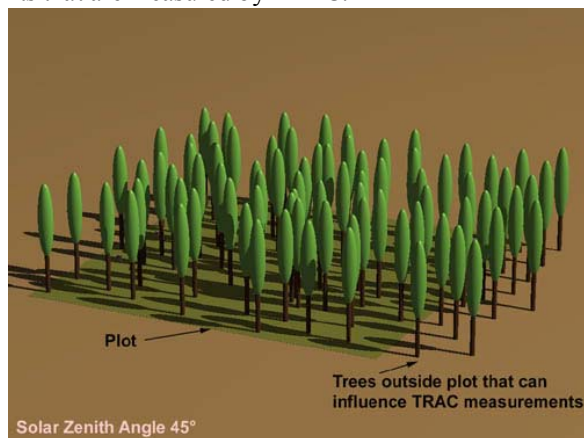


Figure 4.1: The position of the transect in a plot must be considered based on the height of the trees and the solar zenith angle. Trees outside the plot cast shadows inside the plot. This is important when comparing TRAC measurements with other kinds of measurements. Sun is to the right hand side of the image.

If the TRAC measurements are going to be used to validate remote sensing data, the location of the study area and transect is highly important.

Plots need to be easily found on the remote sensing image. Even with a good GPS, a stand may be difficult to pinpoint. It is often better to choose a transect near a road intersection. That way, if you are not sure of the accuracy of the GPS coordinate of the transect, the intersection can be used as a guide to find the site on the image. If you are using a Landsat TM image, your transect should be at least 100 m from the edge of the forest stand, and even further away if the solar zenith angle is large and the sun is on the side of that edge.

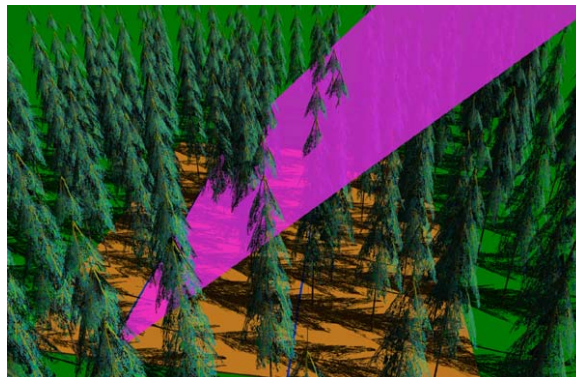


Figure 4.2: All contact points between the pink plane and the foliage represent shadows that are cast on the blue line that represents the TRAC transect walked by the operator. Sun is to the right hand side of the image.

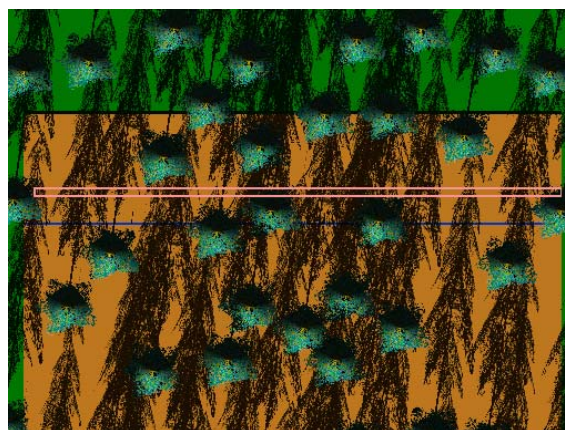


Figure 4.3: Orthographic nadir view of the same transect as Figure 4.2. The blue line is where sunrays in pink are reaching the canopy and background in Figure 4.2. Sun is at bottom of the image.

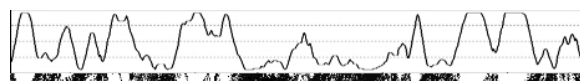


Figure 4.4: The lower part of this figure is the background with shadows represented in a monochromatic mode. It is a transect from the Fig. 4.3, (it simulates the TRAC walked in the pink area). TRACWin computed a clumping index of about 0.5 for this transect.

Orientation of the transect: if the site has to be revisited, either the same day, or at different period of the year, the orientation of the transect is important since the optimal setting has the transect perpendicular to the sun. To be sure that the transect is valid most of the day, a East-West orientation is preferred, but may not be optimal for all cases. If the transect is far from the perpendicular, the width of the element casting the shadows needs to be adjusted with (for spherical leaves, see Eq. 3.24 and 3.25):

$$W_p = W / \sqrt{\frac{\cos^2 \theta + \tan^2 \Delta\beta}{1 + \tan^2 \Delta\beta}} \quad (4.1)$$

When there are no site limitations, a SE-NW direction is usually best for afternoon measurements since usually half a day measurements are needed to cover the solar zenith angle range for site-intensive studies. On sloping grounds, the preferred transect direction would be that parallel to the slope and the measurements time needs to be adjusted accordingly. The reported LAI is then per unit of slope surface area.

4.2 Markers: Once the transect orientation is decided, mark the transect every 10 m (or more if you have very long transect or less for smaller transect) with an easily visible marker (flag or stake; see Figure 4.5).

4.3 Using TRAC with other instruments

As mentioned in 4.1, the footprint of the TRAC needs to be considered when taking the measurements. Other instruments such as LAI-2000 have different footprint. To combine them as suggested in the theory, care must be taken when a stand is not homogeneous. Figure 4.6 is a suggested plot, based on the SibLAI project measurements scheme that combined LAI-2000 with a 90° or 180° view cap, hemispherical photographs (360° view) and typical forestry measurements. The size of 100x100m² was set for optimum comparison with LANDSAT TM 3x3 pixels (90x90m²). This configuration allows a maximum coverage with each instrument with a minimum overlap and LAI estimates from the trees inside the plot (for a stand with tree height around 10-20 m). On this configuration, the TRAC measurement needs to be taken in the morning and LAI-2000 in the evening. This scheme allows few trees outside the plot to be measured by some of the instruments. The centre of the plot has the maximum weight.



Figure 4.5: This photograph shows a transect from a deciduous site where flags were used as markers every 10 m. At the time the photo was taken, the sun was not at an ideal position since it is very close to being parallel to the transect.

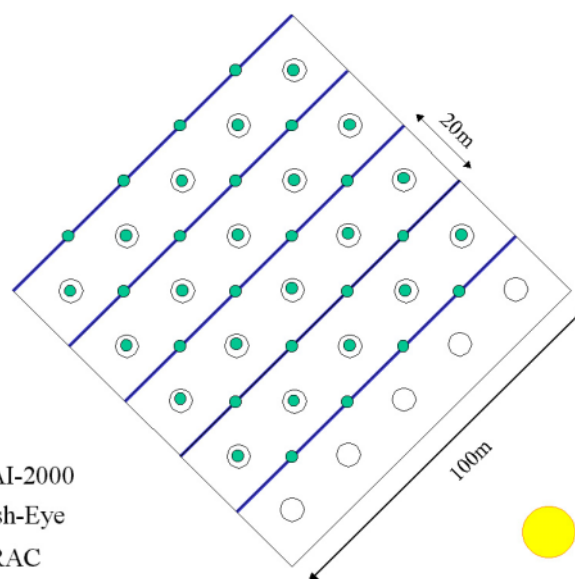


Figure 4.6 Suggested 1 ha plot (based on NASA SIBLAI project) where TRAC is combined with LAI-2000, Fish-Eye (hemispherical) photographs and forestry measurements. Note the morning sun south-east in the Northern hemisphere (North being up).

4.4 Taking the measurements:

TRAC Set up

Before using TRAC, you need to set it up:

- Connect TRAC to a PC, using the 9-pin serial connector and adapter cord supplied with TRAC.
- Switch on TRAC. TRAC should beep twice and emit a clicking signal once per second, indicating STANDBY mode. If TRAC beeps 3 times on power up, disconnect the serial link and replace the 9-volt battery.
- Start TRACOMX (Figure 4.7), press **set up**, the software will ask you to proceed to clear TRAC memory.
- Press Okay: TRAC will beep twice. The instrument is ready for use. Note that the program won't tell you that TRAC was connected properly or not. So make sure that TRAC beeped twice.
- Exit TRACOMX and disconnect TRAC from the computer. Do not turn TRAC off because the internal clock of TRAC only works when TRAC is on. The instrument can be turned off after the data collection.

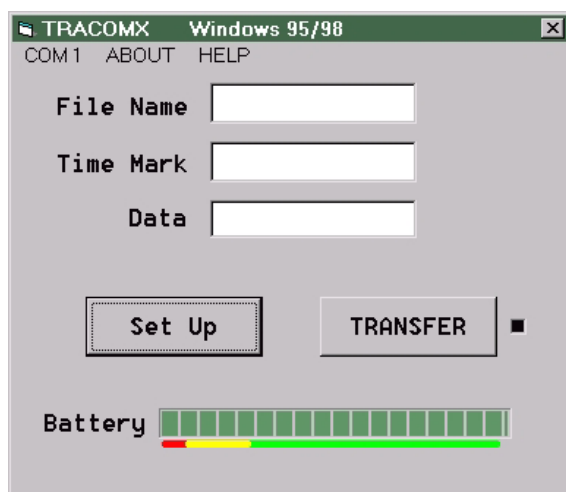


Figure 4.7: Windows-based software TRACOMX. It is the communication software between your PC and TRAC.

TRACOMX creates a file FILE.DAT containing information about the time and date. On some system, the date may not be properly formatted. A valid FILE.DAT should look like this:

```
00412163.TRC
16:20:51
2000-04-12
```

The first line has the name of the file that will contain the TRAC data (default name). The convention is first character for the year (0=2000, 1=2001, ...), the next two digits represent the month (e.g., 04 = April). The next two digits are for the day and the last three the time in decimal hours (16.3 = 4:20 PM). The second line has the set up time and the third line the date. The date needs to be in the YYYY-MM-DD format. Only one TRAC can be set up from TRACOMX in a given directory. Copying TRACOMX to another directory can be used set up more than one TRAC instruments.

DATA Logging

Adjust the sensors angle to the holding arm and hold TRAC at a comfortable distance from your feet, depending on the understory, and the desire to include the understory or not in your data, the height at which you hold TRAC may vary.

Press the control button for 1/2 second or more to go into data logging mode or back into standby mode. Mode change is indicated by one beep and a distinct change in the clicking frequency. To insert a distance/time marker in the data stream (when walking over a flag for example), press the control button momentarily and release.

At the last marker position, press and release the button as usual (less than 1/2 seconds) and then press again the button for a second to stop the measurements. This last step makes the data processing easier.

Sensor travelling speed: with a sampling frequency of 32 Hz for the sensors, a measurements density of one sample per 10 mm can be achieved at a walking pace of one meter per three seconds. For short stands, where the sunfleck size is small, higher spatial sampling density may be necessary and the walking speed needs to be slower. When in doubt, a slower speed is always better, but remember that the precision is limited by the clarity of the smallest discernable shadow and sunfleck (with consideration of the penumbra). Generally, a 10 m segment should have about 1000 datapoints.

Data Transfer

Download the transect measurements as often as possible. We suggest one file for each plot. Connect TRAC to the same PC you did your set up and run TRACOMX again. During the transfer, the filename is displayed, and the sensor readings and time markers are visible in the display window. The data is retained in TRAC memory and can be transferred repeatedly. To clear the TRAC memory for the next session, repeat the set up procedure. Otherwise further login after transfer(s) will append data to the existing file. **Be aware of wrap-around after 45 minutes of logging.**

5. Data Processing

TRAC is distributed with an analysis software (TRACWin) for Microsoft Windows. Updates of TRACWin can be requested by emailing or calling Sylvain Leblanc at the Canada Centre for Remote Sensing: (613) 947-1294, Sylvain.LebLANC@CCRS.NRCan.gc.ca

TRACWin is a stand alone program; you can start it from a floppy disk. An installation program is included with the newer versions. Note that for earlier versions, the name of the file may reflect the release of the program (e.g., TRAC_WIN1.3.3.EXE). The program will install it to your PC and create a link in <Start><CCRS><TRAC><TRAC for Windows>.



Figure 5.1: TRACWin shortcut that can be placed on your desktop.

5.1 What TRACWin does:

The first quantity TRACWin calculates is the gap fraction. This is done for each checked segment with (Chen et al., 1996):

$$P(\theta) = \frac{R_{mean} - R_{Min}}{R_{Max} - R_{Min}} \quad (5.1)$$

where R_{mean} is the mean PPFd reading in a segment, R_{min} is the minimum PPFd in a segment, and R_{max} is the maximum PPFd (above canopy PPFd). The gap fraction of the transect is the mean of the individual segment gap fraction. The minimum PPFd is found as the peak of the histogram for PPFd less than $\frac{1}{4}$ the maximum PPFd. To improve gap fraction estimation, TRACWin calculates the mean reading by forcing values smaller to R_{min} to R_{min} and the value larger than R_{max} to R_{max} .

The gap size distribution is found by looking at the change in PPFd readings. The gap area then sorted and an accumulated gap fraction curve is obtained. Then the gap removal technique is applied until the reduced accumulated gap fraction curve resembles a random curve (see section 3.5 for more details).

5.2 How to use TRACWin:

Click on **Input File** (Figure 5.1) and choose a file. The default extension is *.trc. TRACWin will automatically put a filename in the output field based on the input file you

entered. This output file will have the extension *.lai. The important calculations made with TRACWin will be in the *.lai file. The program also creates two file *.fmr and *.pfl. The right hand side of TRACWin (Figure 5.2) reveals the segments (or blocks) with the number of measurements in each of those segments. A segment represents the measurements taken between pressings of the button.

At the suggested walking pace, about 1000 measurements are taken by TRAC per 10 m. You can view the time at which the segments were taken by pressing **Time**. The two buttons at the bottom can be used if more than 30 segments are found in the file. To view the time series of the data in one, or more segments, checked the desired segment boxes and press **PPFD Plot**. Figure 5.3 is a graphical representation of a segment's PPFd.



Figure 5.1: Input and output file names.

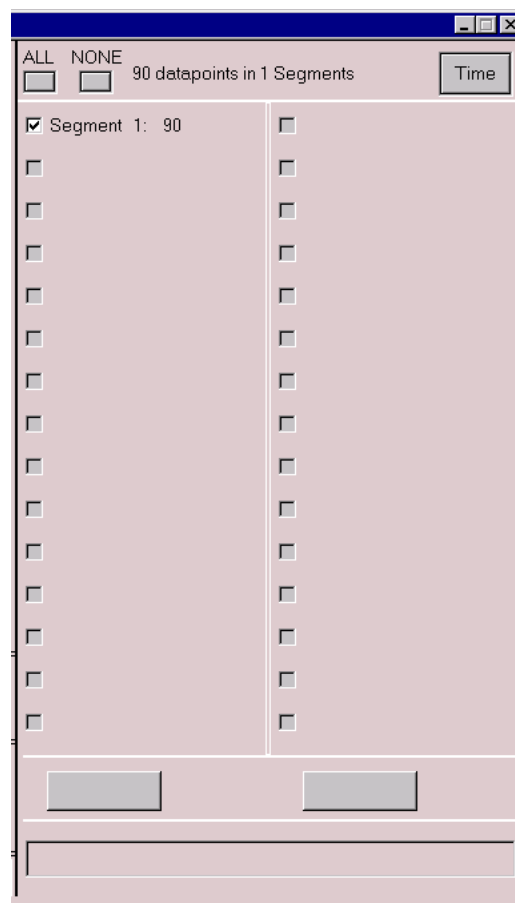


Figure 5.2: Right-hand-side of TRACWin where the segments number and number of datapoints will appear.

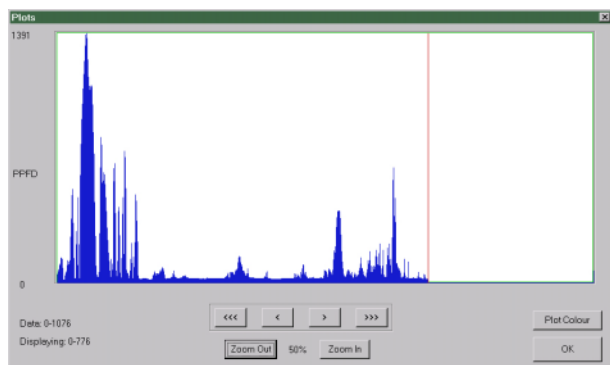


Figure 5.3: PPFD of a segment.

Input File	P:\TRAC\00101068.trc		
Output Files	P:\TRAC\00101068.lai		
Mean Element Width (mm)	50	Exit	
Needle-to-shoot ratio	1	About	
Woody to Total Area Ratio	0	Histogram	
Spacing Between Markers (m)	10		
PPFD Above	1530	<input checked="" type="checkbox"/> Forced	<input type="checkbox"/> Forced Zenith Angle
PPFD Minimum	0	<input type="checkbox"/> Forced	57
Latitude	45	19	0
			<input checked="" type="radio"/> North <input type="radio"/> South
Longitude	75	48	0
			<input type="radio"/> East <input checked="" type="radio"/> West
Time Longitude Reference	75	0	
			<input type="radio"/> East <input checked="" type="radio"/> West
Computer Clock	<input type="radio"/> Reference Time <input checked="" type="radio"/> ReferenceTime +1 hr (summer)		

Figure 5.4: Left hand side of TRACWin where the input parameters are entered.

5.3 What is needed before processing TRAC data?

Different input parameters are to be filled as showed in Fig. 5.4.

- A TRAC file in memory
- Checked one or more segments to process.
- Typical mean element width: It represents the mean size of shadows cast by the canopy. For flat leaves, the

needle-to-shoot ratio is one. For coniferous forests, you need a needle-to-shoot ratio greater than unity in order to consider clumping at scale less than the shoot in coniferous trees. Some typical values (Gower *et al.*, 1999):

- Black spruce (*Picea mariana*): 1.30-1.40;
 - Jack pine (*Pinus Banksiana*): 1.20-1.40;
 - Red pine (*Pinus resinosa*): 2.08,
 - Scots pine (*Pinus sylvestris*): 1.75;
 - Douglas Fir (*Pseudotsuga menziesii*): 1.77
- Woody to total area ratio. A value of zero means that no woody material was "seen" by TRAC. Typical values (Gower *et al.*, 1999):
 - Black spruce (*Picea mariana*): 0.12-0.17;
 - Jack pine (young) (*Pinus Banksiana*): 0.03-0.05;
 - Jack pine (old) (*Pinus Banksiana*): 0.11-0.34;
 - Red pine (*Pinus resinosa*): 0.07,
 - Douglas Fir (*Pseudotsuga menziesii*): 0.08
 - Aspen (*Populus tremuloides*): 0.21-0.22
 - Oak-hickory: 0.11
 - Sitka spruce: 0.23
 - The spacing between markers: The distance between time markers in metres.
 - A PPFD value for the above/outside radiation. If the value for the reference is smaller than any values in the segments used, the value from the segment will be used as the above PPFD, unless "forced" is checked.
 - To obtain a PAIe and LAI values (results will appear at bottom of Windows, see Fig. 5.6), you need the location (longitude and latitude) of the site and the time zone reference longitude. The longitude of the time zone reference is the longitude at which the time, in the time zone the laptop is set, has the exact solar time. It is often a value near the middle longitude of a time zone. For example the EST time zone longitude in North America is at 75°.

1 September 1998	Kme: 1.941	SZA: 56.14 - 55.77 d.
11:29 - 11:39	Gap fraction: 0.144	PAIe: 2.17
W(P): 13.85 mm	OmegaE: 0.96	LAI: 2.26

Figure 5.6: Results area of TRACWin.

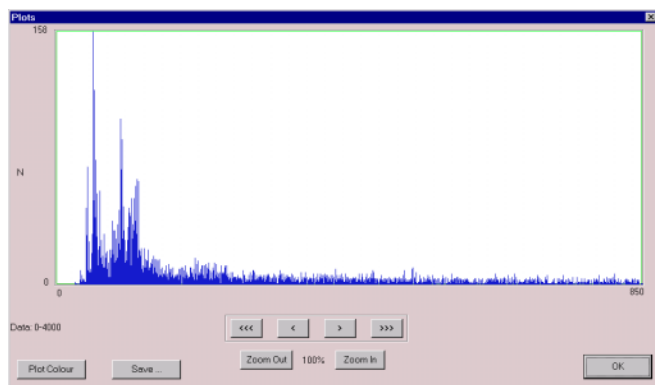


Figure 5.7: Histogram of the PPFD

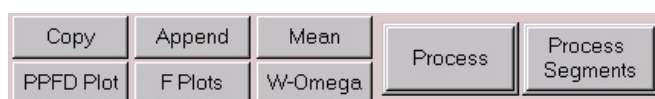


Figure 5.8: Button used to access the different options/capabilities of TRACWin.

5.4 Options of TRACWin:

- **Histogram (Fig. 5.7)**

You can now display and save in an ASCII file the histogram of the checked segments.

- **“Process” and “Process Segments” (Fig. 5.8):**

The segments can be processed alone, or in groups. In the **process by segment** option, each segment is processed separately and the result for each segment is saved in a separate file. The output file (*.sts) has the statistics for the segments and different clumping index are calculated (see output files in section 6). Figure 5.9 shows what results appear when you press **Process**. The date, the time of acquisition, an estimate of W_p (mean element width based on the data using the P approach, the mean contact number **Kmean**, the **gap fraction**, the clumping index (**OmegaE**) at scale larger than the element casting the shadows, the solar zenith angle (**SZA**), the effective PAI and the LAI.

- **Forcing minimum and maximum PPFD**

It can be useful to force the maximum PPFD because a transect may not have gaps large enough to get the maximum PPFD. The minimum PPFD is an option that is useful to check the effect of that variable on the LAI and clumping retrieval. TRACWin finds the minimum PPFD in

each segment by looking at the peak of the histogram in that segment.

- **Forcing Zenith Angle**

This is useful when the time stamps in the TRAC file are wrong. You can force the solar zenith angle to be at that value.

- **Copy Segment(s) (Fig. 5.8):**

Useful if you want to break a large data file into smaller files. Just choose the segments you want to copy and press the Copy Button. It will ask you for a file name.

- **Append Segment(s) (Fig. 5.8):**

Useful to append two transects of the same plot to be analysed together. It allows TRACWin to be a TRAC file manager with the combined **Copy** and **Append** options.

- **Compute Mean of Segment (s):**

Useful for computing the mean PPFD of a segment. If you have a reference segment, you can then use that value as the maximum PPFD.

- **F Plots, W-OMEGA**

Plots of F_{mr} , F_r and F_m (Figure 5.9), or plot Omega (Ω_E) in function of the input foliage width (Figure 5.10).

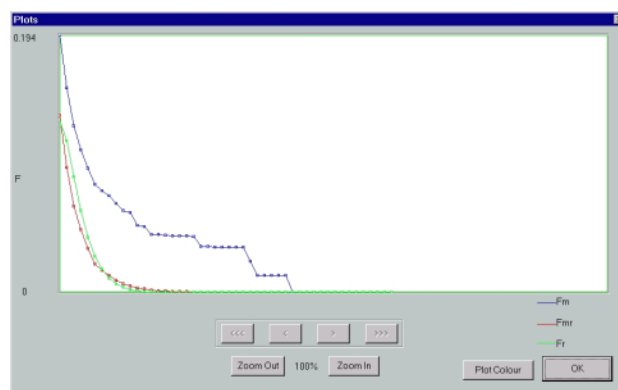


Figure 5.9: F_m , F_{mr} and F_r curves based on data and typical element size.

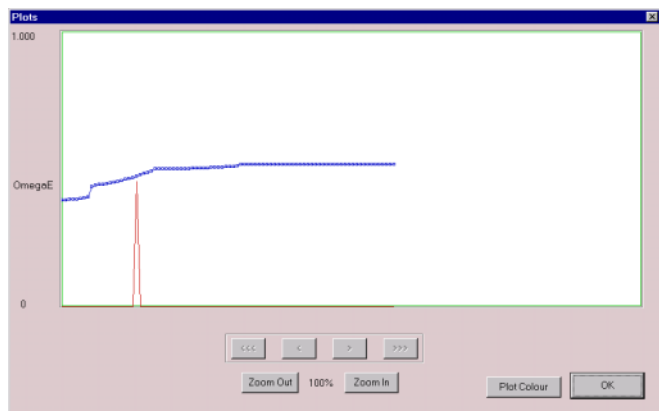


Figure 5.10: W-Omega: Plots the variations of the clumping (omega) versus the input foliage width. The red line points to the clumping index (omega) based on the element width used as input parameters.

5.5 VERSIONS

Latest version: 2.5.3 (September 2002)

The latest versions also include the possibility to use TRACWin with digital hemispherical photographs. A complete new manual will be available shortly to explain how to analysed hemispherical photographs.

Recent changes:

2.5 (March-August 2002)

Added options for Digital Hemispherical Photographs study. Reset block view when opening file. Automatically put in grey coordinates when using forced zenith angle.

2.3.3 (February 27, 2002): Small change in creation of names for Segments process.

2.3.3 (February 13, 2002):

Solved a bug in the creation of output files in "process by segment" when file names had more than one "." in them. Gap fraction that was zero is now unity in *.sts when there is no foliage is a segment.

2.3.1 (January 24, 2002)

The histogram can be saved. Minimum PPFd can be forced.

2.3.0 (January 10, 2002)

Added histogram view capability. Added an append mode.

2.2.1 (December 2001)

Added Lang and Xiang (1986) Lai and clumping in segment processing option. TRACWin now calculates a PPFd histogram for each segment. Each histogram is used to find PPFd min in each segment. Improved the processing of

segments separately. Added line indicating the max PPFd on graphs to help find the best maximum PPFd.

2.1.3 October 2001

Important change to theory (Δg).

Better handling of large gaps

Re-addition and modification of "forced" PPFd

Addition of Append block

Changed display of LAIe to PAIe (effective plant area index)

Changed display of Kme to Kmean (mean contact number)

TRAC_DOS.EXE (or TRAC.EXE)

The DOS version should no longer be used because it has not been updated since 1999 and newer versions of Microsoft Windows do not allow old DOS software to run properly. Please use TRACWin.

6. OUTPUT FILES

TRACWin normal processing creates three kinds of output files. The date, version of the software, and the blocks used are included as a header for later reference.

6.1 xxxxxxxx.lai, this file gives the element clumping index and the mean contact number at various foliage element widths. The values corresponding to the input element width are marked by "--this is the clumping index you need":

File created on October 22, 2001 from file P:\TRAC\JAMESBAY\Wem5.trc with TRAC Windows Version 2.1

Data taken on August 18, 1998

Block used: 13, 14, 17, 19, 20, 21, 24, 25, 26, 27

Mean element width: 30.0 mm

Needle-to-shoot ratio (GammaE): 1.00

Woody to total ratio (ALPHA): 0.00

Distance between markers: 10.00 m

Above PPFd: 1641.0

Latitude: 53.000° 0.000' 0.0" North

Longitude: 80.000° 43.000' 0.0" West

Long Ref: 75.000° 0.000' West

Longitude reference time + 1 hour

Mean interval resolution at sensor 1.17 cm

This file provides clumping index OmegaE at various characteristic leaf widths in mm and the mean contact number Km

$Kme = G(SZA) \text{ OmegaE LAI} / (\text{GammaE} * \cos(SZA))$

We can therefore obtain LAI by assuming $G(\text{all angles})=0.5$:

$\text{LAI} = 2 Kme \cos(\text{theta}) / \text{Omega}$

For this stand, the effective mean contact number $Kme =$

2.97

Width Km Old OmegaE New OmegaE

10 2.878 0.689096 0.703568

11 2.873 0.690480 0.704907

12

...

30 2.331 0.851005 0.859426 -- This is the clumping index you need

31 2.307 0.859837 0.867857

32 2.278 0.870620 0.878136

33 2.256 0.879371 0.886464

....

Mean Solar Zenith Angle in the transect = 58.66

LAIe= 2.06 LAI= 2.42

W from data: 47.129 mm

6.2.xxxxxxxx.fmr, this file contains the values of measured gap size distribution ($F_m(\lambda)$), the processed gap size distribution after the gap removal procedure ($F_{mr}(\lambda)$), and the gap size distribution for the random case ($F_r(\lambda)$). This output file gives details of canopy architectural information and can be used to understand how the clumping index was calculated. It is also useful for ecological and radiation modelling concerning canopy gap size such as the duration of leaf illumination in the canopy and on the forest floor, and directional reflectance modelling (see Chen and Leblanc, 1997). Example:

File created on April 25, 2000 from file File created on October 22, 2001 from file

P:\TRAC\JAMESBAY\Wem5.trc

TRAC Windows Version 2.1

These are the final results of gap size distribution of

Fm Fmr Fr

Element width equals 30

Lambda Fm Fmr Fr

0 0.139458 0.088130 0.086256

10 0.114813 0.063486 0.069240

20 0.093283 0.041956 0.044347

30 0.076531 0.025244 0.025671

40 0.063074 0.014661 0.014028

50 0.050895 0.008617 0.007384

60 0.043032 0.005636 0.003787

...

6.3 xxxxxxxx.pfl, this file provides the probability of a probe of length l falling completely into a sunfleck underneath the canopy (P(l)) at various values of l (or λ).

P(l) can also be used to compute the clumping index and several canopy architectural parameters using the "P approach" (Chen and Black, 1992; Chen and Cihlar, 1995a). This file is more useful for researchers who are trying to

advance LAI calculation theories and use gap size information for other purposes.

File created on October 22, 2001 from file

P:\TRAC\JAMESBAY\Wem5.trc

TRAC Windows Version 2.1

This file is the output of l in mm, P(l) and F(l) and W(P(l))

0 0.137583011 0.13758301129

10 0.090319584 0.11319200545 47.13

20 0.065042703 0.09191591118 63.24

30 0.048421332 0.07537002672 72.60

40 0.036724645 0.06208812259 79.51

50 0.028568668 0.05008233175 91.57

6.4 xxxxxxxxxx.sts this file is created by the "process segments" option. The sts stands for statistics as the file contains results from individual xxxxxxxxxx.lai files. The file also contains these results:

Mean PAIe: 2.233

Mean LAI: 2.429

Mean Gap fraction: 0.189

PAIe: 2.173

OMEGA(T): 0.854

OMEGA(L): 0.973

OMEGA(T+L): 0.895

OMEGA(M) 0.916

Mean gap fraction is the mean gap fraction of the segments (same values than "process"). PAIe is the effective plant area index calculated using the mean gap fraction. Mean PAIE is the mean effective plant area index of the segments; mean LAI is the mean leaf area index. Mean LAI is calculated by finding the clumping index within segments and adjusting the PAIe of each segment by its clumping index and woody material before calculating the average. OMEGA(T) is the usual clumping index found by analysing all segments checked at once (Ω_E). OMEGA(L) is found by comparing the mean PAIe to PAIe (Lang's method). OMEGA(T+L) is found by comparing the mean PAI to PAIe (TRAC + Lang methods). OMEGA(M) is the mean clumping index from each segment.

7 FREQUENTLY ASKED QUESTIONS

7.1 How to determine the leaf or foliage element width?

For broadleaf's, a general equation for calculating the leaf width is

$$\bar{W} = \sqrt{G(\theta)A} \quad (7.1)$$

where A is the projected (one-sided) leaf area. For crops and natural canopies, $G(\theta) = 0.5$ is valid in many cases, especially if the solar zenith angle is near 57.3° . To get A , you can digitise a leaf contour, or if the leaf is almost circular, use its diameter (d) and approximate it as being a disc ($A = \pi(d/2)^2$) (Fig. 7.1). TRACWin can be used to get an estimate of W_p by using the "P" approach (section 3.7).

For coniferous trees, assuming the shoot can be approximated by a cylinder, $A = \pi(dL + 0.5d^2)/2$ where L is the length of the cylinder and d the diameter.



Figure 7.1 Schematic representation of approximation of the projected leaf area A .

7.2 How does the azimuthal angle difference between the sun and the transect influence the final calculation and can it be corrected?

The effect is usually small. If the elements are spheres with the sun at 45° , the effect is within 25% when the angle difference between the sun and the transect is more than 30° . Because of this small effect, the angle difference is not considered in the data processing software TRACWin in order to minimise the input requirement, but for measurements at large solar zenith angle and a small angle difference between the sun and the transect, assuming spherical object, the width for spherical leaves should be calculated as

$$W_p = W / \sqrt{\frac{\cos^2 \theta + \tan^2 \Delta\beta}{1 + \tan^2 \Delta\beta}}, \quad (7.2)$$

where W_E is the value found with equation 7.1, θ is the solar zenith angle and $\Delta\beta$ is the azimuthal angle difference

between the sun and the transect. For leaves that can be approximated by a cylindrical shape, the calculation is:

$$W_p = W / \sin \Delta\beta \quad (7.3)$$

7.3 Has the penumbra effect on the sunfleck been considered in the calculation?

Yes, the details are given in Chen and Cihlar (1995b). This allows a gap resolution better than the "at sensor" resolution that depends on the walking speed of the operator.

7.4 What should I do if I missed a distance marker during measurements?

It doesn't matter, TRACWin will recognise this from the double length of a segment in the record and automatically insert a marker in the middle of the segment. The same principle is used to break up sections in which more than one distance marks are missed. But if too many markers are missed for a short transect, it can be a problem. In that case, we suggest editing the data file and inserting manually marks were needed. Mark lines start with 9999 and contain the time of acquisition.

7.5 What happens if I accidentally press the button between two markers while taking measurements?

You should keep going as usual. You can either delete the time marker in the data stream from the raw data file before doing the calculation or ignore this section by not choosing it while running TRACWin. In TRACWin a mispressed button can be automatically determined.

7.6 Can I stop during the measurements and restart from where I stopped?

Yes. The segments do not need to be continuous in the data file. One way to continue if you have to stop during measurements (e.g. because of a passing cloud): press the button for two seconds and go back to the last flag and start from there.

7.7 Will I loose data if I turn off TRAC?

No. You loose data if you reset the memory, or if you reach the end of the memory at which point the new data is erasing the oldest data.

7.8 I can't transfer data to the computer, why (using old TRACOM.EXE only)?

Although the transfer process is very simple, a bad setting of your computer may result in long delays. Make sure that your laptop has no problems transferring the data before going into the field. The program used for the data transfer is TRACOM.EXE. It needs two files to work properly: PORT.CFG and FILE.DAT. PORT.CFG contains information about the communication system (port) and the second has the set up information (time and date). Some recent laptops running under Windows 95 and 98 have problems accessing the communication port under DOS. On some systems, you can solve this problem by creating a shortcut to TRACOM.EXE and specifying the kind of DOS it will start. Once the shortcut is created, right-click on it and go to properties. Go to the Program tab. Once there, enter the working directory (where the data will be transferred). Press the Advanced button, checked MS-DOS mode and specify a new DOS configuration. The following set up worked on most PCs:

CONFIG.SYS:

```
DOS=HIGH,UMB
Device=C:\WINDOWS\Himem.Sys
DeviceHigh=C:\WINDOWS\EMM386.Exe
device=C:\WINDOWS\cwbininit.exe/W
AUTOEXEC.BAT:
SET TMP=c:\windows\TEMP
SET TEMP=c:\windows\TEMP
set PROMPT=$p$g
SET winbootdir=C:\WINDOWS
SET WIN32DMIPATH=C:\DMI\
```

Note that this configuration does not work on IBM Thinkpad laptops.

We strongly suggest the use of TRACOMX.EXE for PC with Windows 95 and up.

7.9 TRACWin crashes or stops when I press "PROCESS", why?

Although TRACWin has been tested with many canopy conditions, it is always possible that a combination of parameters outside the normal range of use could crash the program. Please contact us if the problem persists.

7.10 Why do I get many segments with only 16 datapoints?

The 16-datapoint segments are made when you press the button during 1/2 second to stop the acquisition. 0.5 times 32 Hz = 16 points.

7.11 What is/are the optimal solar zenith angle to take measurements?

The preferred range of solar zenith angle is from 30 to 60 degrees. If the transect is far from being perpendicular to the sunrays, then the best is to have the sun high in the sky. One other aspect to consider is the foliage angular distribution that is represented by the function $G(\theta)$. Random orientation of the foliage, i.e. $G(\theta) = 0.5$, is assumed by TRAC to compute LAI. Although the measured values of $G(\theta)$ are usually close to 0.5, variations exist and can induce errors in the LAI calculation. Eq. 3.10 suggests using TRAC at 57.3° , when feasible. $G(57.3^\circ)$ is always very close to 0.5, independent of LAI and clumping. For very dense canopy, it is possible that there will not be enough transmission of sunrays through the canopy for gap distribution at high SZA. In that case, smaller values of solar zenith angle are preferred.

7.12 How to combine LAI-2000 or hemispherical photographs measurements with TRAC measurements.

This can be done several ways. But the preferred way is best represented by:

$$L_t = - \frac{\sum_{i=1}^n \frac{2}{\Omega(\theta_i)} \cos(\theta_i) \sin(\theta_i) \ln(P(\theta_i))}{\sum_{i=1}^n \sin(\theta_i)} \quad (7.4)$$

It may be difficult, but the preferred way involves averaging the gap fraction of individual rings at angle θ_i because the clumping is calculated over the whole stand and thus the clumping is the difference between the stand as if it was filled with randomly distributed foliage element and the actual clumped stand. This can be checked by comparing the gap fraction from TRAC at the solar zenith angle and the closest ring of the LAI-2000. The clumping can either be assumed to be constant, thus the same value is used at each θ_i . Or, the clumping index dependency on the zenith angle θ_i can be used. This can be done by measuring the clumping at several angles, or by using a functional approximation (linear, quadratic, etc). That way a regression can be obtained by assuming that $\Omega(\theta)$ goes near unity at 90° . Another way is by using Eqs. (3.9) or (3.10), both are basically equivalent to (Chen 1996; Chen et al., 1997a):

$$L = -2 \frac{(1 - \alpha)}{\Omega(\theta_E)} L_{et}, \quad (7.5)$$

where L_{et} can be calculated from gap fraction at θ_E or from all angles using Miller's theorem.

7.13 How to transfer data from TRAC to a different PC that the one used for set up?

The set up process does two things: 1) it resets the memory array of TRAC to zero, and 2) it saves the time and date of the set up. Once the set up is done, the TRAC starts counting time. So if another PC is used for the transfer, the time will be counted from a different beginning. On the second PC, you can edit (or create) the file FILE.DAT and change the date and time to the one that would have been on the other PC. If the data is already downloaded, you will need to edit the *.trc file and change all time stamps. You can either do it manually, or write a small routine in your favourite programming language to do that. Since the time is mainly used to get the solar zenith angle, you can calculate the solar zenith angle of your transect and use the **Forced Zenith Angle** option.

7.14 What is the footprint of TRAC?

To know the footprint of TRAC, the only required inputs are the solar zenith angle and the height of the trees. Figure 7.2 is a representation of TRAC's footprint over a transect.

Extend of the footprint = height of trees times $\tan(\theta)$

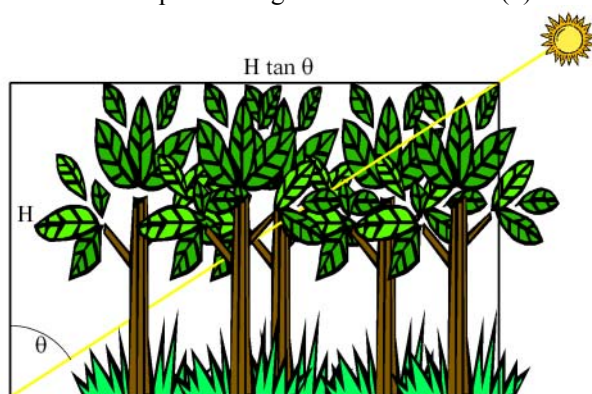


Figure 7.2 Extent of TRAC measurements

8. Partial List of symbols

Name	Acronym	Symbol
Leaf Area Index	LAI	L
Total Plant Area Index	PAI	L_t
Effective Leaf Area Index	LAIE	$L_e(\theta)$
Effective Plant Area Index	PAIE	$L_{et}(\theta)$
Woody Material Area Index	WAI	M
Effective Woody Material Area Index	WAIe	$M_e(\theta)$
Foliage Clumping Index from all scales	FCI	$\Omega(\theta)$
Foliage element Clumping Index	FCI _E	$\Omega_E(\theta)$
Woody Material Clumping Index	WCI	$\Omega_W(\theta)$
Needle to shoot ratio (clumping index scale less than shoot)	-	γ_E
Foliage Element Projection coefficient	-	$G(\theta)$
Apparent Foliage Element Projection coefficient ($=G(\theta)\Omega_E(\theta)$)	-	$G_A(\theta)$
Zenith Angle; Solar Zenith Angle; View Zenith Angle	ZA; SZA; VZA	$\theta; \theta_s; \theta_v$
Equivalent Miller's theorem (view or solar) Zenith Angle	ZA _E	$\theta_E \sim 57.3^\circ$
Sunlit leaf area index	-	L_{su}
Shaded leaf area index	-	L_{sh}
Woody to total plant area index	-	α

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