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Leaf area index (LAI) and gap fraction. A discussion

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Abstract

Methodological aspects of estimating leaf area from gap fraction measurements are discussed. Instead of the common practice of linking in the Beer-Lambert law leaf area index and clumping factor together, the clumping factor and Ross-Nilson geometry function as two structure parameters should be combined into the effective geometry function, which considers both the leaf angle distribution and clumping/regularity of foliage in the expression of the gap fraction of a vegetation layer.

Keywords: leaf area index; foliage clumping; gap fraction; LAI-2000; G-function

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As a sheet of paper has an area (and it is simple to measure), the area of a plant leaf can also be measured. In principle, we can cut and measure the area of every leaf over a study plot and sum them together to get the total area of leaves over a study plot. The ratio of this total area of leaves to the plot area is the leaf area index (LAI) of the vegetation canopy on this plot (LI-COR 2023b). LAI is a primary characteristic of the vegetation layer.

Collecting leaves and measuring their area is not a very practical method for measuring LAI of a plant stand, and practically not applicable in a forest. There are numerous papers on how to estimate LAI of a grassland, a crop field, or a broadleaf forest. It may not be necessary to list such papers here.

Optical methods of measuring LAI are based on the link between the LAI and gap fraction in the view direction (Li-Cor 1989, LI-COR 2023a, and several others). The link between the LAI and gap fraction is provided in the well-known paper by Tiit Nilson published in 1971 (Nilson 1971). The point quadrat analysis by Warren Wilson (1960) as a method to measure the LAI and gap fraction is also described in that paper. In a foliage layer, where the following assumptions are fulfilled (the Poisson model), the layer transparency (gap fraction) and the LAI of this layer are linked with an exponential expression, also known as the Beer-Lambert law. The assumptions are the following:

- The layer consists of a very large number, N, of statistically independent horizontal sub-layers, each having a thickness of $\Delta L = L / N$, where L is the LAI of the whole foliage layer.
- The probability of observing more than one contact within a small layer, ΔL, is infinitely small compared with the probability of one contact.
- The probability of observing a contact within a small layer, ΔL, is equal to the mean number of contacts per layer in the point quadrat method of vegetation analysis, $m_x(\Delta L, \theta) = G(\theta)\Delta L/\mu$, where: $\mu = \cos(\theta)$, θ is the zenith angle of view direction, $G(\theta)$ is the Ross-Nilson geometry function, the projection of the unit area of foliage in the view direction, i.e.:

$$G(\theta) = \frac{1}{2\pi}\int_{2\pi} g_L(\theta_n)\,|\cos\widehat{rr}_n|\,\sin\theta_n\,d\theta_n\,d\phi_n, \qquad (1)$$

where $g_L(\theta_n)/2\pi$ is the foliage normal's distribution function, θ_n and ϕ_n are the polar and azimuth angles of a leaf normal, respectively, $\widehat{rr}_n$ is the angle between view direction and leaf normal.

The probability of no contacts in the layer, ΔL (the transparency of the layer, ΔL, at the zenith angle θ) is $P_0(\Delta L, \theta) = 1 - G(\theta)\Delta L/\mu$.

In such a canopy layer, the probability of seeing through the canopy in direction θ – the gap fraction – is:

$$P_0(\theta) = \exp(-G(\theta)L/\mu) \qquad (2)$$

These three assumptions are not fulfilled in vegetation canopies. Plant leaves are not infinitely small, and the foliage layer cannot be divided into a very large number of statistically independent horizontal sub-layers. Also, leaves may be relatively close to each other so that the distance between them may be of the same order as leaf dimensions, or leaves may even touch each other in a canopy. Nilson (1971) analysed the link between the LAI and gap fraction if the assumptions of the Poisson model are not fulfilled. The first attempt was to consider the dependence of leaf positions in adjacent layers as a Markov chain. That led to the inclusion of an additional parameter of the layer structure, the grouping/regularity parameter, λ_0, into the gap fraction expression Eq. (2),

$$P_0(\theta)=\exp(-\lambda_0 G(\theta) L/\mu) \quad (3)$$

In a random structure (Poisson pattern of foliage), $\lambda_0=1$. If foliage is grouped to some extent, $\lambda_0<1$, and if the pattern of foliage is regular to some extent, $\lambda_0>1$. The clumping factor, λ_0, is an indirect measure of overlapping of leaves in the view direction. In a grouped structure, the overlapping is greater than in the Poisson structure, and in a regular structure, the overlap is smaller – leaves tend to fill gaps in the foliage layer. The clumping factor, λ_0, may also be the function of view angle, $\lambda=\lambda(\theta)$. If we only measure the angular variations of gap fraction, we cannot distinguish whether they are caused by variations of G-function or clumping factor, or by simultaneous change of both.

Jing Chen has analysed in numerous papers the clumping of foliage. In their papers, Chen et al. (1991) and Black et al. (1991) grouped λ_0 and L in Eq. (3), and called it "effective leaf area index". Since then, the term "effective leaf area index" has been used when describing optical methods of estimating the leaf area of vegetation canopies, which are based on the measurement of gap fraction.

This definition of effective leaf area index is incomprehensible. What is such an effective leaf area index effective for? The effectiveness of leaf area (or a fraction of the contributing foliage area) depends on the process we are analysing. The effective leaf area in photosynthesis, transpiration and evaporation, forming turbulent air flow, and the interception of incident radiation, may be different. Van Leeuwen et al. (2013) wrote: "Abstracting the actual crown morphology introduces […] model parameters that are effective in describing canopy radiation […], yet their actual real-life meaning is lost. An example of such a parameter is the effective LAI that provides for the application of the Beer-Lambert Law to clumped canopies, but its value does not equate to the real canopy LAI".

There were numerous uses of the term "effective leaf area" with different meanings for different purposes during years before the paper by Chen et al. (1991). Lemeur and Rosenberg (1979) define effective leaf area index as the part of leaf area which intercepts radiation in the view direction,

$$\Delta L_{eff}=\Delta L<\cos(\alpha)>\mu\ , \quad (4)$$

where ΔL is the LAI of a sublayer, Δz, α is the angle between leaf normal and view direction, and angle brackets denote averaging over azimuth. The same definition of effective leaf area index was used by Daynard (1969). Yang et al. (2017) use terms "Visible Fraction of Leaf Area", "Visible Leaf Area Index, VLAI", and "Sunlit Leaf Area Index". These are terms which describe which part of leaf area is effective for the interception of radiation. When talking about effective leaf area, it is necessary to define for what process the leaf area is effective.

The LAI is the measure of foliage amount in the canopy. If we rearrange the foliage of random pattern to the clumped or regular pattern then the LAI does not change, but transparency of the layer and consequently the area of shadows changes because the overlapping of leaf projections changes – changes the projection of leaf area: $G(\theta)\rightarrow G_{eff}(\theta)=\lambda(\theta)\,G(\theta)$. Especially awkward is to talk about the changing (effective) LAI with changing view direction.

Both the Ross-Nilson G-function, $G(\theta)$, and the clumping factor, $\lambda(\theta)$, are the characteristics of the geometrical structure of the layer – the leaf angle distribution (LAD) of foliage determines the G-function, and the pattern of leaf positions may be random, regular, or clumped, as described by the clumping factor. Instead of grouping together LAI and clumping factor, $\lambda(\theta)$, and $G(\theta)$ should be grouped in Eq. (3), and the combined parameter, $G_{eff}(\theta)=\lambda(\theta)\,G(\theta)$, can be called "effective projection" or "effective G-function". The effective G-function, $G_{eff}(\theta)=\lambda(\theta)\,G(\theta)$, considers both the leaf angle distribution and overlapping of leaf projections (of leaf shadows in direct radiation).

Equation (3) allows estimating the LAI from the measured gap fraction,

$$L=-\mu\ln(P_0(\theta))\,/\,(\lambda(\theta)\,G(\theta)) \quad (5)$$

As it is challenging to estimate the LAD, which determines the G-function (Eq. (1)), both the clumping factor and G-function may be unknown in Eq. (5). The accuracy of the LAI value estimated this way depends on how well we know the values of the G-function and clumping parameter for the view direction, θ. If we use incorrect values for $G(\theta)$ and $\lambda(\theta)$, we get a biased estimate of the LAI.

The plant canopy analyser (PCA) LAI-2000/2200 (Li-Cor 1989, LI-COR 2023a) measures gap fraction simultaneously at five zenith angles. While new versions of PCA (LAI-2200C) have updated controller and the updated software includes corrections of gap fraction for scattered radiation under direct sunlight, the PCA optics and measurement principle is that of LAI-2000 (LI-COR 2023b). In processing gap fraction data, the LAI and mean leaf angle are estimated simultaneously. The Poisson structure is assumed, which is equivalent to using $\lambda(\theta)=\lambda_0=1$ in Eq. (5). $G(\theta)$ values for five view directions are calculated assuming the constant LAI and clumping factor. If the canopy structure deviates from the Poisson structure, the mean value of clumping factor is moved to the left side of Eq. (5), defining "effective LAI" as $LAI_{eff}=\lambda_0 L$. Therefore, *de facto* standard instrument of optical LAI measurements the LAI-2000/2200 (Li-Cor 1989) returns in non-Poisson structures the biased LAI estimate, which is called "effective LAI", while not clarifying for what is such LAI estimate effective. This way, the unknown clumping/regularity of foliage is hidden into “effective LAI”.

Another problem is that if the clumping parameter, λ_0, is not constant but is a function of view zenith angle θ, $\lambda = \lambda(\theta)$, then instead of estimating $G(\theta)$, the angular dependence of the effective G-function $G_{eff}(\theta) = (\lambda(\theta) / \lambda_0)\, G(\theta)$ is estimated by the processing algorithm. Thus, the possible changes of clumping factor with the zenith angle are hidden in the G-function.

The same problems persist, if digital hemispherical photos are used instead of LAI-2000/2200 ones for the LAI measurements. Having only gap fraction data, we do not know is the LAI estimate correct or biased.

Much work has been done to correct such biased LAI estimates and convert the “effective LAI” to the “true LAI”. All such methods are based on some assumptions about the character of foliage pattern, and the accuracy of the result depends on how accurate the assumptions are. It may happen that such corrections just hide the reason of bias deeper.

The term “effective LAI” is misleading. It does not specify what it is effective for. The so-called “effective LAI” may be biased estimate of LAI and having only gap fraction data we do not know, is it biased or not. In case it is biased, we do not know, is the bias caused by the unknown clumping/regularity of the foliage pattern or by the wrong estimate of the leaf angle distribution (the G-function), or the bias is caused by both. In recent years terrestrial laser scanners have become available and can be used for analysing the canopy structure. The point clouds of high-volume density allow, along with gap fraction in all directions in the upper hemisphere, to measure the LAD (Kuusk 2020) and quantitatively estimate clumping of foliage (Kuusk et al. 2018, Zhu et al. 2018). This makes the estimation of the LAI of a vegetation canopy more accurate.

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References

Black, T.A., Chen, J.M., Lee, X. and Sagar, R.M. 1991. Characteristics of shortwave and longwave irradiances under a Douglas-fir forest stand. *Canadian Journal of Forest Research* 21: 1020–1028.

Chen, J., Black, T. and Adams, R. 1991. Evaluation of hemispherical photography for determining plant area index and geometry of a forest stand. *Agricultural and Forest Meteorology* 56: 129–144.

Daynard, T. 1969. The quality of shortwave radiation within plant canopies. *Canadian Journal of Botany* 47: 1989–1994.

Kuusk, A. 2020. Leaf orientation measurement in a mixed hemiboreal broadleaf forest stand using terrestrial laser scanner. *Trees* 34: 371–380; https://doi.org/10.1007/s00468-019-01922-6.

Kuusk, A., Pisek, J., Lang, M. and Märdla, S. 2018. Estimation of gap fraction and foliage clumping in forest canopies. *Remote Sensing* 10: 1153; https://doi.org/10.3390/rs10071153.

Lemeur, R. and Rosenberg, N. 1979. Simulating the quality and quantity of short-wave radiation within and above canopies. In: Halldin, S. (Ed.) Comparison of Forest Water and Energy Exchange Models. Copenhagen: International Society for Ecological Modelling, p. 77–100.

LI-COR. 1989. LAI-2000 Plant Canopy Analyzer. Technical Information. LI-COR, Inc. URL: https://www.licor.com/env/support/LAI-2000/home.html (accessed: 26 June 2023).

LI-COR 2023a. LAI-2200C Plant Canopy Analyzer. LI-COR Biosciences GmbH. URL: https://www.licor.com/env/products/leaf_area/LAI-2200C/ (accessed: 26 June 2023).

LI-COR. 2023b. Theory of Operation. In: LI-2200C Plant Canopy Analyzer. LI-COR Biosciences GmbH. URL: https://www.licor.com/env/products/leaf_area/LAI-2200C/science (accessed: 26 June 2023).

Nilson, T. 1971. A theoretical analysis of the frequency of gaps in plant stands. *Agricultural Meteorology* 8: 25–38.

Van Leeuwen, M., Coops, N.C., Hilker, T., Wulder, M.A., Newnham, G.J. and Culvenor, D.S. 2013. Automated reconstruction of tree and canopy structure for modelling the internal canopy radiation regime. *Remote Sensing of Environment* 136: 286–300; https://doi.org/10.1016/j.rse.2013.04.019.

Warren Wilson, J. 1960. Inclined point quadrats. *New Phytologist* 59: 1–8.

Yang, B., Knyazikhin, Y., Mõttus, M., Rautiainen, M., Stenberg, P., Yan, L., Chen, C., Yan, K., Choi, S., Park, T., Myneni, R. 2017. Estimation of leaf area index and its sunlit portion from DSCOVR EPIC data: Theoretical basis. *Remote Sensing of Environment* 198: 69–84; https://doi.org/10.1016/j.rse.2017.05.033.

Zhu, X., Skidmore, A., Wang, T., Liu, J., Darvishzadeh, R., Shi, Y., Premier, J. and Heurich, M. 2018. Improving leaf area index (LAI) estimation by correcting for clumping and woody effects using terrestrial laser scanning. *Agricultural and Forest Meteorology* 263: 276–286; https://doi.org/10.1016/j.agrformet.2018.08.026.