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Specular reflection in the signal of LAI-2000 plant canopy analyzer

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ABSTRACT

In a vegetation canopy part of leaves reflect sky radiation specularly to the LAI-2000 sensor. This fraction is smaller in a planophile canopy and higher in an erectophile canopy. As the specularly reflected radiation does not enter the leaf nor it is absorbed by leaf pigments and depending on the incidence angle on the leaf the reflection coefficient may be very high. Depending on the leaf area index (LAI) and leaf angle distribution the scattered sky radiation may cause an overestimation of the gap fraction and consequently an underestimation of LAI up to 20–25% if the LAI measurements with plant canopy analyzer LAI-2000 are carried out under ideal perfectly overcast conditions. Similar biases are present in measurements of gap fraction and LAI with hemispherical photos if these measurement procedures are calibrated against LAI-2000. Considering the scattered sky radiation in optical techniques (LAI-2000, hemispherical photos) of measuring gap fraction in vegetation canopies explains at least part of the observed discrepancies in gap fraction estimated with terrestrial laser scanner and hemispherical photos. The scattered sky radiation in the LAI-2000 signal introduces bias both in the estimated LAI and foliage clumping index.

1. Introduction

The plant canopy analyzer (PCA) LAI-2000 has been in use for the non-destructive determination of leaf area index (LAI), and other structural attributes of vegetative canopies for about 25 years (Li-Cor, 1989). The PCA uses the gap fraction technique for the calculation of LAI and mean inclination angle of foliage. New models of the PCA by Li-Cor Inc. (LAI-2200C) have new versions of the control unit and software, but the principle of measurements and the optical sensor are not changed. The instrument is considered the world standard for indirect LAI measurements (Li-Cor, 2014).

Methods for estimating LAI using hemispherical (digital) photos (HP) are developed. The main problem in using hemispherical photos for the gap fraction and LAI measurements is precisely distinguishing sky and foliage pixels in images (Song et al., 2014). The PCA LAI-2000 (LAI-2200C) is used as the reference in calibrating methods which use hemispherical photos (Leblanc et al., 2005; Garriques et al., 2008).

The LAI-2000 computes an estimate of LAI for a vegetative canopy from measurements of light interception made at five angles simultaneously. The main assumptions that must be met for the LAI calculation to be correct, in approximate order of importance, are (Li-Cor, 1989, 2014):

1. The foliage absorbs all light that is incident upon it.
2. The foliage elements are small compared to the area of view of each ring of the PCA.
3. The foliage is randomly distributed within certain foliage containing envelopes. Then the probability to see sky through the canopy $t(\theta)$ (gap fraction) at zenith angle θ and leaf area index L are linked according to the Beer–Lambert law
$$t(\theta) = \exp(-G_L(\theta)L/\cos\theta), \tag{1}$$
where $G_L(\theta)$ is the Ross-Nilson geometry function – the mean projection of unit foliage area in the direction of view angle θ,
$$G_L(\theta) = \frac{1}{2\pi}\int_{2\pi} g_L(\theta_n)\cos\theta_n \sin\theta_n d\theta_n d\phi_n, \tag{2}$$
$g_L(\theta_n)/2\pi$ is the distribution function of the foliage normal, θ_n and ϕ_n are the polar and azimuth angles of a leaf normal, respectively.
4. Foliage is azimuthally randomly oriented.

Violation of these assumptions results in errors of the estimated LAI values. The violation of the assumption 2 causes random errors which can be suppressed by repeating measurements. This kind of errors has been analyzed by Nilson and Kuusk (2004).

The violation of the assumption 4 can be avoided by using view restrictors (Li-Cor, 1989).

The violation of the assumption 3 brings along systematic bias in the estimated LAI values. There are numerous studies about

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clumping and regularity in foliage pattern and avoiding bias in LAI measurements with LAI-2000 and hemispherical photos in such canopies (Smith et al., 1993; Stenberg, 1996; Nilson, 1999; Leblanc et al., 2005; Demarez et al., 2008, and several others).

Less attention has been paid to the violation of the assumption 1 – to the light scattering off of canopy elements. It is recommended to carry out measurements in overcast conditions and to use view restrictors when operating in direct sunlight.

Kobayashi et al. (2013) developed basic theory of light scattering in a vegetation canopy for consideration in PCA measurements. Based on their analysis, Kobayashi et al. (2013) provide suggestions for the correction of LAI estimates for the measurements in direct sunlight.

In this study the role of specular reflection of sky light on foliage is analyzed in case LAI-2000 measurements are carried out under ideal perfectly overcast conditions.

2. Theory

Plant canopy analyzer LAI-2000 uses hemispherical optics and a ringed silicon detector in the image plane. The hemispherical image is projected onto five concentric sensor elements corresponding to five zenith angle ranges. Light readings are made below a canopy. A reference reading is made above the canopy. The ratio of ring signals under canopy and above canopy provides the gap fraction at mean zenith angles 7°, 23°, 38°, 53°, and 68°,

$$t(\theta_j) = \frac{b_j(L)}{b_j(0)}, \tag{3}$$

where $b_j(L)$ is the signal of the ring j under canopy, and $b_j(0)$ is the signal of this ring above the canopy, θ_j is the mean zenith angle of the ring j. Leaf area index L is calculated from the angular profile of gap fraction $t(\theta_j)$ (Li-Cor, 1989)

$$L = -2\int_0^{\pi/2} \ln(t(\theta))\cos\theta\sin\theta\, d\theta. \tag{4}$$

The sensor rings are sensitive in the wavelength range between 320 and 490 nm (blue light). In this spectral range the absorption of leaf pigments makes foliage almost non-transparent, and reflection coefficient of leaves is less than 5%. The assumption of the LAI calculations is that the below-canopy incident radiation does not include any radiation that has been reflected or transmitted by foliage,

$$b(\theta) = b_s(\theta)t(\theta) \tag{5}$$

where $b_s(\theta)$ is the sky radiance at zenith angle θ.

Then the signal of the PCA ring j is proportional to the fraction of sky visible through the canopy,

$$b_j(L) = c_j \int_{\Delta\theta_j} b_s(\theta)t(\theta)\cos\theta\, d\theta, \tag{6}$$

where $\Delta\theta_j$ is the angular width of the ring j, and c_j is the calibration coefficient of the ring j, gap fraction $t(\theta)$ is defined in Eq. (1).

In the perfect overcast conditions the sky radiance $b_s(\theta)$ at zenith angle θ is calculated according to the ISO-15469 standard (ISO, 2004)

$$b_s(\theta)/b_s(0) = (1 + \exp(-0.7/\cos\theta))/2.986, \tag{7}$$

where $b_s(0)$ is the sky radiance in zenith.

The angular profile of the relative sky radiance of overcast sky is plotted in Fig. 1.

In a vegetation canopy part of radiation incident on a leaf does not enter the leaf and is not absorbed by leaf pigments – it is reflected from the leaf surface according to the Fresnel law (Vanderbilt and Grant, 1985; Comar et al., 2012)

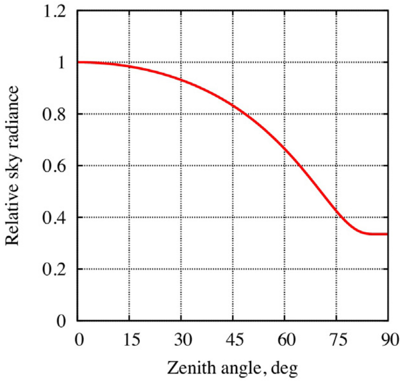

Fig. 1. Angular profile of the overcast sky radiance according to the ISO-15469 standard.

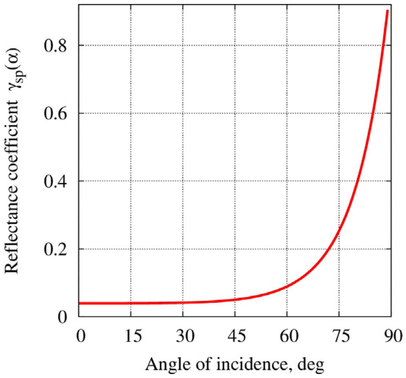

Fig. 2. Angular profile of Fresnel's reflectance, $n_i = 1.5$.

$$\gamma_{sp}(\alpha) = \frac{1}{2}\left(\frac{\sin^2(\alpha - i)}{\sin^2(\alpha + i)} + \frac{\tan^2(\alpha - i)}{\tan^2(\alpha + i)}\right), \tag{8}$$

where α is the polar angle of incident radiation on leaf, $i = \sin^{-1}(\sin(\alpha)/n_i)$, n_i is the refraction index of the epicuticular wax of a leaf. In the spectral sensitivity range of LAI-2000 sensor both the sky radiance and sensor sensitivity decrease with decreasing wavelength, but the value of refraction index increases, therefore in the following model calculations the value of refractive index at 490 nm $n_i = 1.5$ is used (Vanderbilt and Grant, 1985; Jacquemoud and Baret, 1990). Dependence of the leaf specular reflectance on the incidence angle is plotted in Fig. 2.

If leaves are strictly horizontal all the specularly reflected sky radiation is reflected back to the upper hemisphere. In a canopy of randomly oriented leaves, some leaves can reflect toward the sensor most of the sky radiation which is incident on the leaf from the direction $s = (\theta_s, \phi_s)$.

To find the direction of incident radiation on a leaf which is specularly reflected to the sensor in direction $j = (\theta_j, \phi = 0)$, the local coordinates $(\bar{x}, \bar{y}, \bar{z})$ are introduced so that the normal of the leaf is directed along the $\bar{z}$-coordinate and the $\bar{x}$-coordinate is rotated relative to the ground coordinates for the leaf normal's azimuth angle ϕ_n. In these local coordinates the components of the sky vector $\bar{s}$ and view vector $\bar{j}$ are symmetrical: $\bar{s}_x = -\bar{j}_x$, $\bar{s}_y = -\bar{j}_y$, $\bar{s}_z = \bar{j}_z$.

To find the sky vector $s = (\theta_s, \phi_s)$ in ground coordinates, first, the view vector $\bar{j}$ in local coordinates $(\bar{x}, \bar{y}, \bar{z})$ is found by the rotation of coordinates about z-axis by angle ϕ_n and about y-axis by angle θ_n,

$$\bar{j} = \mathbf{R}_y\mathbf{R}_z j. \tag{9}$$