On the correct estimation of gap fraction: How to remove scattered radiation in gap fraction measurements?

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Abstract

Correct estimates of gap fraction are essential for quantifying canopy architectural variables, such as leaf area and clumping indices, which modify land–atmosphere interactions. However, gap fraction measurements from optical sensors are contaminated by radiation that is scattered by plant elements and ground surfaces. In this study, we propose a simple one-dimensional, invertible, bidirectional transmission model to remove scattering effects from gap fraction measurements. To evaluate how well the proposed model computes scattered radiances under a variety of ecosystem conditions, we compared simulated scattered radiances by the proposed model to a more sophisticated three-dimensional model in four ecosystem types (oak-grass savanna, birch, pine, and spruce stands). The simple model showed good agreement with the three-dimensional model in the scattering factor (scattered radiation from leaves normalized by sky radiation), except for highly reflective stems such as birch. The simple model showed that the scattering factor is highest when the leaf area index (LAI) is low (1–2 m² m⁻²) in a non-clumped canopy, potential errors in estimating the LAI increase with an increase in LAI, and bright land surfaces (e.g., snow and bright soil) and bright stems (e.g., birch) can contribute significantly to scattering effects. By applying the simple model with LAI-2200 data collected in an oak-grass savanna woodlot, we found that the scattering factor causes significant underestimation of the LAI (up to 26% for sunny conditions, 7.7% for diffuse sky conditions) and significant overestimation of the apparent clumping index (up to 14% for sunny conditions, 4.3% for diffuse sky conditions). The LAI is underestimated because of the effect of scattered radiation on gap fraction estimates, which cause overestimation of the clumping index. Even under highly diffuse sky conditions, errors in LAI estimates due to scattering effects are not always negligible (up to 7.7% underestimation). The proposed inversion scheme provides an opportunity to quantify gap fractions, LAI, and apparent clumping index even under sunny conditions.

1. Introduction

The estimation of gap fraction allows one to infer canopy architectural variables such as leaf area index (LAI) (Wilson, 1971; Ross, 1981; Ryu et al., 2012; Welles and Norman, 1991), apparent clumping index (Ryu et al., 2010), and distribution of leaf inclination angle (Lang, 1986; Norman and Campbell, 1989). Canopy architectural variables influence land–atmosphere interactions and thus have direct impacts on climate (Chase et al., 1996; Dickinson et al., 1998; Ryu et al., 2011). In spite of several decades of gap fraction studies (Acoc et al., 1970; Anderson, 1966; Neumann and Den Hartog, 1989; Warren Wilson, 1959), correctly estimating the gap fraction remains a challenging task.

Canopy transmittance is the sum of uncollided and scattered radiation hence the real gap fraction is less than the measured value. This scattering effect of canopies makes it difficult to accurately estimate gap fractions using optical sensors, which are widely used. Because LAI is deduced by inverting gap fraction measurements (Miller, 1967), the inversion process will be biased if transmitted radiation through the canopy is augmented by scattered radiation. Optical gap fraction estimates are based on the assumption that leaves are black (i.e., there is no scattering).
Nomenclature

\(\alpha\)  \quad\text{zenith angle of a leaf surface normal direction}

\(\alpha_0\)  \quad\text{angle between the sun and leaf normal}

\(\beta\)  \quad\text{azimuth angle of a leaf surface normal direction}

\(\gamma\)  \quad\text{shoot clumping}

\(\Gamma\)  \quad\text{scattering transfer function}

\(\Gamma_{\text{bmn}}\)  \quad\text{scattering transfer function for beam (}\approx\Gamma_D + \Gamma_{\text{SP}}\)

\(\Gamma_D\)  \quad\text{scattering transfer function, diffuse scattering of beam on leaf surface}

\(\Gamma_{\text{SP}}\)  \quad\text{scattering transfer function, specular reflectance of beam on leaf surface}

\(\Gamma_{\text{dif}}\)  \quad\text{scattering transfer function for diffuse radiation}

\(\phi\)  \quad\text{evaluation function for inversion}

\(\mu\)  \quad\text{leaf absorptivity}

\(\tau\)  \quad\text{plant canopy optical thickness}

\(\theta_s\)  \quad\text{solzenith angle (}0 < \theta_s < 90\text{ degree)}

\(\theta_v\)  \quad\text{view zenith angle (}0 < \theta_v < 90\text{ degree)}

\(\varphi_{\text{wvc}}\)  \quad\text{Azimuth angle of opening in LAI-2200 with a narrow view cap}

\(\varphi_{\text{v}}\)  \quad\text{relative view azimuth to solar azimuth angle}

\(\varphi_s\)  \quad\text{solazimuth angle}

\(\varphi_v\)  \quad\text{view azimuth angle}

\(\omega\)  \quad\text{single scattering albedo (=}R_{\text{LD}} + R_{\text{LS}} + T_{\text{LD}}\text{)}

\(\Omega(\theta)\)  \quad\text{clumping index at } \theta

\(\Omega_{\text{mean}}\)  \quad\text{mean clumping index over the solar zenith angle } \theta_s

\(\alpha(L)\)  \quad\text{constant for forest floor reflectance}

\(f\)  \quad\text{correction factor of Fresnel reflectance}

\(f_{\text{dAd}}\)  \quad\text{correction factor of adaxial leaves}

\(f_{\text{bm}}\)  \quad\text{fraction of beam incident radiation above canopy}

\(f_{\text{dif}}\)  \quad\text{fraction of diffuse incident radiation above canopy}

\(f_\text{up}(\theta,\varphi,\alpha,\beta)\)  \quad\text{fraction of leaf area with a leaf normal of } (\alpha,\beta)

\(f_{\text{bnm}}\)  \quad\text{above-canopy beam irradiance perpendicular to the sun direction (}W \text{ m}^{-2}\text{)}

\(F_{\text{tot}}\)  \quad\text{total incident solar irradiance perpendicular to horizontal plane (}W \text{ m}^{-2}\text{)}

\(g(\alpha)\)  \quad\text{leaf angle distribution function}

\(G(\theta)\)  \quad\text{fraction of projected leaf area perpendicular to } \theta

\(h\)  \quad\text{canopy height}

\(I_{\text{dif}}\)  \quad\text{incident diffuse radiance integrated over the upper hemisphere (}W \text{ m}^{-2}\text{)}

\(I_{\text{f}}\)  \quad\text{incident radiance at canopy floor integrated over the upper hemisphere (}W \text{ m}^{-2}\text{)}

\(I_\text{bd}(\theta,\varphi,\psi_r)\)  \quad\text{scattered radiance (}W \text{ m}^{-2} \text{ str}^{-1}\text{)}

\(I_\text{bd}(\theta,\varphi,\psi_r)\)  \quad\text{scattered radiance of beam (}W \text{ m}^{-2} \text{ str}^{-1}\text{)}

\(I_{\text{ld}}(\theta,\varphi,\psi_r)\)  \quad\text{scattered radiance of diffuse (}W \text{ m}^{-2} \text{ str}^{-1}\text{)}

\(I_{\text{eff}}\)  \quad\text{reflected radiance from the forest floor (}W \text{ m}^{-2} \text{ str}^{-1}\text{)}

\(I_{\text{sky}}(\theta,\varphi,\psi_r)\)  \quad\text{diffuse sky radiance (}W \text{ m}^{-2} \text{ str}^{-1}\text{)}

\(k\)  \quad\text{empirical parameter for the specular reflectance correction factor } f

\(K_{\text{be}}(\theta_s)\)  \quad\text{beam extinction coefficient (=}G(\theta_s)\text{)}

\(K_{\text{de}}\)  \quad\text{extinction coefficient for diffuse radiation}

\(L\)  \quad\text{LAI at the arbitrary height in plant canopy}

\(L_{\text{c}}\)  \quad\text{total canopy LAI}

\(L_{\text{e}}\)  \quad\text{effective LAI}

\(n\)  \quad\text{leaf surface refractive index}

\(O_{\text{wvc}}(\theta,\varphi,\psi_r)\)  \quad\text{sky radiance measured by LAI-2200 with a narrow view cap}

\(O_{\text{wvc}}(\theta,\varphi,\psi_r)\)  \quad\text{sky radiance measured by LAI-2200 with a wide view cap}

\(P(\theta,\varphi,\psi_r)\)  \quad\text{scattering phase function}

\(P_0(\theta,\varphi,\psi_r)\)  \quad\text{true gap fraction}

\(P_{0,0}(\theta,\varphi,\psi_r)\)  \quad\text{measured gap fraction (including a scattered radiation)}

\(r_{sp}\)  \quad\text{Fresnel reflectance (average of the parallel and perpendicular polarized radiation)}

\(R_{\text{F}}\)  \quad\text{forest floor black sky albedo}

\(R_{\text{w}}\)  \quad\text{forest floor white sky albedo}

\(R_{\text{LD}}\)  \quad\text{leaf diffuse reflectance factor}

\(R_{\text{LS}}\)  \quad\text{leaf specular reflectance factor}

\(R_{\text{stem}}\)  \quad\text{stem reflectance factor}

\(S(\theta_s,\theta_v,\psi_r)\)  \quad\text{scattering factor}

\(S_{\text{sky}}=t\)  \quad\text{scattering factor of a black forest floor condition}

\(T_d(L)\)  \quad\text{diffuse transmittance}

\(T_{\text{LD}}\)  \quad\text{leaves transmittance factor}

\(\nu\)  \quad\text{leaf area density (}m^2\text{ m}^{-3}\text{)}

\(x\)  \quad\text{leaf angle parameter for ellipsoidal leaf angle distribution}

For example, the LAI-2000 Plant Canopy Analyzer (or LAI-2200, referred to hereafter as LAI-2200; LI-COR Biosciences, Lincoln, NE) assumes black leaves using a blue band (320–490 nm), within which leaves absorb the most radiation (Welles and Norman, 1991). In fact, leaves are not completely black; they transmit and reflect light even in the blue band (Gates et al., 1965). Because of scattered radiation from leaf surfaces, it has been recommended that these optical instruments (LAI-2200 or digital hemispherical photography) be used under fully diffused sky conditions, such as overcast days or near sunset or sunrise. This condition imposes a logistical limit on sample size (Leblanc and Chen, 2001), and assumes that scattered radiation from the canopy can be ignored under diffused sky conditions. However few studies have tested the validity of this assumption.

Leblanc and Chen (2001) proposed a semi-empirical correction scheme to take account of the scattering effect in gap fraction measurements. However, this method only considers the zenith angle dependency of the scattering effect and ignores azimuthal scattering anisotropy because it assumes that a wide view cap is used (270° field of view) (Leblanc and Chen, 2001). However, caps with narrower view (e.g., 45° field of view) are necessary to accurately estimate the apparent clumping index and LAI from a LAI-2200 (Nilson et al., 2011). Thus, it is essential to consider the scattering effect in the azimuthal direction.

To quantify radiation scattered from a canopy, a simple invertible bidirectional transmission model that integrates the scattered radiation under a given plant canopy condition (angular distribution of incoming radiation, leaf reflectance, leaf transmittance, leaf inclination distribution, LAI, and clumping index), is necessary. To date, a number of plant canopy bidirectional reflectance models have been proposed (Combal et al., 2003; Kobayashi and Iwabuchi, 2008; Li and Strahler, 1992; Wanner et al., 1995; Widlowski et al., 2007), but few have been applied to gap fraction analysis (Kallel et al., 2008; Nilson, 1999; Nilson et al., 2011). From the perspective of remote sensing, bidirectional reflectance models are more meaningful because remote sensing captures land surface reflectance. However, from the perspective of measuring gap fraction under canopies, the development of a simple invertible bidirectional transmittance model is warranted.

The LAI-2200 sensor has been widely used in numerous studies since the early 1990s (Chason et al., 1991; Gower and Norman, 1991; Law et al., 2001; Welles and Cohen, 1996; Welles and Norman, 1991). The instrument estimates key canopy architectural variables, including gap fraction, mean leaf inclination angle, and
LAI. It is notable that the instrument considers some extent of foliar clumping effects (apparent clumping index) by applying Lang’s method (Lang and Xiang, 1986; Ryu et al., 2010a), which computes actual LAI rather than effective LAI. However, the impact of scattered radiation on gap fraction measurements with the instrument can cause biases in estimating LAI and the clumping index.

In the present study, we developed and tested a method for removing scattering effects of canopies to obtain correct gap fraction estimates. The proposed method is a simple, practical one-dimensional bidirectional transmittance model. We compared it to a three-dimensional (3D) bidirectional transmittance model in a wide range of ecosystem types and applied it to gap fraction data collected in an oak-grass savanna ecosystem for which reliable LAI and clumping index data are available. The scientific questions addressed in this paper include: How can scattering effects be removed? Which factors contribute to scattering effects?

2. Methods

Measurements of canopy transmittance contain direct beam and radiation scattered by leaves and woody elements. Under these conditions, the measured gap fraction $P_{0,mes}$ can be written as:

$$P_{0,mes}(\theta_s, \phi_s, \psi_s) = P_0(\theta_s, \phi_s, \psi_s) + S(\theta_s, \phi_s, \psi_s)$$

where $\theta_s$, $\phi_s$, and $\psi_s$ are the sun and the sensor view zenith angles, and the relative azimuth angle between the sun ($\phi_s$) and sensor view directions ($\psi_s$). All symbols are defined in the Nomenclature. $P_0(\theta_s)$ is the true gap fraction with no scattering effects. $S(\theta_s, \phi_s, \psi_s)$ is the scattering factor that corrects the true gap fraction. $S(\theta_s, \phi_s, \psi_s)$ is expressed as radiance scattered by leaves $I_s$ (W m$^{-2}$ str$^{-1}$) normalized by the sky radiance $I_{sky}$ (W m$^{-2}$ str$^{-1}$):

$$S(\theta_s, \phi_s, \psi_s) = \frac{I_s(\theta_s, \phi_s, \psi_s)}{I_{sky}(\theta_s, \phi_s, \psi_s)}$$

The LAI-2200 can measure $I_{sky}(\theta_s, \phi_s, \psi_s)$ at the top of the canopy. $I_s$ can be evaluated by radiative transfer modeling as explained below. True gap fraction can be computed by:

$$P_0(\theta_s, \phi_s, \psi_s) = P_{0,mes}(\theta_s, \phi_s, \psi_s) - S(\theta_s, \phi_s, \psi_s)$$

2.1. Simple invertible bidirectional transmission model

To estimate LAI from $P_{0,mes}$, we developed a simple invertible bidirectional transmission model. We assumed that the plant canopy was one-dimensional. The effect of woody elements was ignored; the only scattering medium was assumed to be leaves. The effect of spatial heterogeneity among the leaves on light penetration was considered using the clumping index $\Omega$ (Nilson, 1971). Because leaf reflectance and transmittance are normally low (<0.06) in the blue spectral domain (320–490 nm) (Gates et al., 1965) where the LAI-2200 measures $P_{0,mes}$, the single scattering component is dominant.

2.1.1. Single scattering approximation with clumping effect

A single scattering approximation for a plant canopy was derived by Ross (1981) based on atmospheric radiative transfer modeling. However, his model did not consider the clumping effect when assuming a turbid medium in the plant canopy. According to Ross (1981), the single scattering approximation of the radiative transfer equation is:

$$\cos \theta_s \frac{dl}{d\tau} = -1 + \frac{\omega}{4\pi} P(\theta_s, \phi_s, \psi_s) F_{bm} e^{-\tau/cos \theta_s},$$

where $F_{bm}$ is the above-canopy beam irradiance perpendicular to the sun direction; $F_{bm} e^{-\tau/cos \theta_s}$ is the intercepted beam component; $I$ is radiance perpendicular to the horizontal plane. $\omega$ is the single leaf scattering albedo and the sum of leaf diffuse reflectance factor ($R_D$), leaf specular reflectance factor ($R_S$), and transmittance factor ($T_L$); $\tau$ is the optical thickness of the plant canopy, and $P$ is the scattering phase function normalized as $1/(4\pi) \int_0^{2\pi} \! \! \int_0^{\pi} P(\theta_s, \phi_s, \psi_s) \! sin \theta_s d\theta_s d\phi_s = 1$. For a clumped canopy, $\tau$ can be expressed as a function of LAI:

$$\tau = \int_0^h u \Omega(\theta) G(\theta) dz = L \Omega(\theta) G(\theta),$$

where $u$ is leaf area density (m$^2$ m$^{-3}$), $L$ is the LAI, $G$ is mean leaf projection perpendicular to the direction of the photon path ($\theta$) and is called the G-function, $\Omega(\theta)$ is the clumping index. The derivative form of equation (5) is:

$$d\tau = \Omega(\theta) G(\theta) dL.$$ (6)

By substituting (5) and (6) into (4) and replacing the intercepted beam radiation from $F_{bm} e^{-\tau/cos \theta_s}$ with $F_{bm} \Omega(\theta_s) e^{-\tau/cos \theta_s}$ for clumped canopies, we obtain:

$$\cos \theta_s \frac{dl}{d\tau} = -1 + \frac{F_{tot} \Omega(\theta_s) G(\theta)}{4 \pi cos \theta_s}$$

where $F_{bm}$ can be expressed in terms of the irradiance $F_{tot}$ perpendicular to the horizontal plane as $F_{bm} = F_{tot} G \cos \theta_s$, where $F_{tot}$ is total irradiance perpendicular to the horizontal plane, and $F_{bm}$ is a fraction of beam irradiance. Equation (7) can be expressed by the differential equation of LAI (1):

$$\frac{dL}{L} = -\frac{\Omega(\theta_s) \Omega(\theta)}{\cos \theta_s} + \frac{F_{tot} \Omega(\theta)}{4 \pi \cos \theta_s \cos \theta} \times \Omega(\theta_s) G(\theta) (\Omega(\theta_s) G(\theta))^{-1}.$$ (8)

Here, the first term on the right side is the penetration of beam radiation and the second term is the contribution from scattered radiation. The scattering phase function $P$ is the probability distribution function of the angular variability of scattering intensity. $P$ is characterized by three scattering events: leaf diffuse reflectance ($R_D$), leaf diffuse transmittance ($T_L$), and leaf specular reflectance ($R_S$). For plant canopy radiative transfer, the scattering transfer function $\Gamma$ is more commonly used (Ross, 1981; Shultis and Myneni, 1988). There is a relationship between $P$ and $\Gamma$ (Shultis and Myneni, 1988):

$$\frac{\omega P(\theta_s, \phi_s, \psi_s, \psi_s)}{4\pi} = \Gamma(\theta_s, \phi_s, \psi_s)$$

(9)

The scattered radiation at the canopy depth [$L$, $L + dL$] is written as:

$$dI_{sc} = \frac{F_{tot} \Omega(\theta_s) G(\theta)}{\cos \theta_s} \times \frac{\Gamma(\theta_s, \phi_s, \psi_s, \psi_s)}{4 \pi \cos \theta_s} \times \Omega(\theta_s) G(\theta) dL.$$ (10)

Here, $I_{sc}$ attenuates via a plant canopy by $e^{-\Omega(\theta_s) G(\theta)(L-L)/\cos \theta_s}$, therefore, the observable radiation at the bottom of the canopy is:

$$dI_{sc} = \frac{F_{tot} \Omega(\theta_s) G(\theta)}{\cos \theta_s} \times \frac{\Gamma(\theta_s, \phi_s, \psi_s, \psi_s)}{4 \pi \cos \theta_s} \times \Omega(\theta_s) G(\theta) \times e^{-\Omega(\theta_s) G(\theta)(L-L)/\cos \theta_s} dL.$$ (11)

2.1.2. Scattering transfer function with specular reflection

The general form of the scattering transfer function $\Gamma_{bm}$ has been well investigated (Ross, 1981; Shultis and Myneni, 1988). To
address the problem of the effect of scattering radiance on gap fraction, both diffuse and specular reflections from leaf surfaces should be incorporated. According to the Fresnel theory of specular reflectance, specular reflectance increases when the incident angle of incoming radiation increases. In plant canopies, this condition occurs when solar elevation is high and the leaf inclination angle distribution is eucrophile (includes many vertical leaves). Thus, $\Gamma_{bm}$ is the sum of diffuse $\Gamma_D$ and specular $\Gamma_{SP}$ components:

$$\Gamma_{bm} = \Gamma_D + \Gamma_{SP}$$

For $\Gamma_D$, we employed a bi-Lambertian approach for a given leaf inclination angle distribution function ($g(\alpha)$) and leaf diffuse reflectance factor ($R_{LD}$) and transmittance factor ($T_{LD}$) (Shultis and Myneni, 1988):

$$\Gamma_D = \frac{H_T + H_R}{2\pi},$$

where,

$$H_T = -T_{LD} \int_0^{2\pi} \int_0^{\pi/2} F(\theta_s, \varphi_s, \alpha, \beta) F(\theta_s, \varphi_s, \alpha, \beta) g(\alpha) d\alpha d\beta$$

and

$$H_R = R_{LD} \int_0^{2\pi} \int_0^{\pi/2} F(\theta_s, \varphi_s, \alpha, \beta) F(\theta_s, \varphi_s, \alpha, \beta) g(\alpha) d\alpha d\beta.$$

The ratio of projected leaf area to actual leaf area with the zenith angle of leaf normal ($\alpha$) and the azimuth angle of leaf normal ($\beta$) in the direction of the sun is given by:

$$F(\theta_s, \varphi_s, \alpha, \beta) = \cos \theta_s \cos \alpha + \sin \theta_s \sin \alpha \cos (\varphi_s - \beta)$$

The ratio of projected leaf area with $\alpha$ and $\beta$ in the sensor view direction, $F(\theta_s, \varphi_s, \alpha, \beta)$, can also be given by the same equation by replacing $\theta_s, \varphi_s$ with $\theta, \varphi$. The product of $F(\theta_s, \varphi_s, \alpha, \beta)$ and $F(\theta_s, \varphi_s, \alpha, \beta)$ represents an estimate of the contribution of leaves that both receive beam radiation and are viewed by the sensor (Fig. 1).

The scattering transfer function for the specular component ($\Gamma_{SP}$) was computed using the method of Vanderbilt and Grant (1985) and Nilson (1990).

$$\Gamma_{SP}(\theta_s, \varphi_s, \theta, \varphi) = \frac{1}{8} g(\alpha) f(\alpha_0) r_{SP}(\alpha_0),$$

where $\alpha_0 = \cos^{-1}(\bar{r}_{S0}/\bar{r}_{S1})$, and $f$ is a correction factor for Fresnel reflectance. Because a leaf reflectance is not perfectly flat, this factor is needed to reduce the influence of Fresnel reflectance (Vanderbilt and Grant, 1985). $r_{SP}$ is the average of parallel and perpendicular polarized radiation to the leaf surface. Most existing studies of leaf specular reflection follow the Fresnel theory. Kuusk (1995) provided an approximation to the Fresnel equation that is more computationally efficient (e.g. Vanderbilt and Grant, 1985). To calculate Fresnel reflectance, a leaf refractive index ($n$) is required. We used $n = 1.3$ according to a previous experimental study (Gausman et al., 1974). The empirical form of the correction factor $f$ was proposed (Nilson and Kuusk, 1989). We modified their model by considering the sides of leaves (abaxial or adaxial) and stem scattering effects. When measuring downward radiance, there is a greater probability of detecting scattered radiation from the adaxial side of leaves, which is less flat with leaf hairs and rugged veins, and thus has lower specular reflectance. Therefore, the factor $f$ should account for the different leaf sides (abaxial or adaxial). In addition, when measuring gap fractions from larger viewing angles, there is a greater probability of detecting the scattered radiation from stems, which are less flat and have lower Fresnel reflectance. Considering these effects, we propose a modified equation for $f$:

$$f(\alpha_0) = \frac{\cos \theta_s \cos \alpha + \sin \theta_s \sin \alpha \cos (\varphi_s - \beta)}{2 \cos \alpha_0 \sin \alpha},$$

where $k$ is an empirical parameter to control the correction factor $f$. Nilson and Kuusk (1989) and Kuusk (1995) used value of 0.01–0.3, and $k = 0$ indicates a perfectly flat surface. In the present study, we used $k = 0.15$. $f_{adaxial}$ is an additional correction factor for the adaxial side. When $f_{adaxial} = 1$, both the abaxial and adaxial sides have the same characteristics. When $f_{adaxial} < 1$, the adaxial side is rougher and has lower specular reflection. The leaf side (adaxial or abaxial) can be deduced from the leaf inclination angle, which is determined using the equation of Card (1987):

$$\alpha = \cos^{-1} \left( \frac{\cos \theta_s + \cos \theta_s}{2 \cos \alpha_0} \right)$$

and

$$\beta = \cos^{-1} \left( \frac{\sin \alpha_0 + \sin \theta_s \cos \varphi_s}{2 \cos \alpha_0 \sin \alpha} \right).$$

If $0 < \alpha < \pi/2$, specular reflection occurs on the adaxial (top) side, and if $\pi/2 < \alpha < \pi$, it occurs on the abaxial (bottom) side. $f_{adaxial}$ in equation (16) varies among plant species. For crop leaves such as corn and rice, there is little difference between the abaxial and adaxial sides of leaves. In such cases, $f_{adaxial} = 1$. In contrast, most tree species show distinct differences in leaf surface flatness ($f_{adaxial} < 1.0$).

2.1.3. Approximation of diffuse sky and intra-canopy scattered radiation

We derived the single scattering of beam radiation analytically (Sections 2.1.1 and 2.1.2). For diffuse sky and intra-canopy scattering radiation, we used an empirical approach to avoid multiple integrations and to make it faster to invert.

The attenuation of diffuse radiation was approximated using Goudriaan’s approach (Goudriaan, 1977), in which the transmission through the canopy depth at L is reduced by leaf absorption $\mu$ ($=1 - R_{LD} - R_{LS} - T_{LD}$):

$$T_d(L) = e^{-\sqrt{\pi} \Omega_{mean} K_{de} L},$$

where $\Omega_{mean}$ is the mean clumping index from a viewing zenith angle of 0–90° and is computed by $2 \int_0^{\pi/2} \Omega(\vartheta) \cos \vartheta_0 \sin \vartheta_0 d\vartheta_0$. $K_{de}$ is an extinction coefficient for diffuse sky radiation. Note that this equation is only valid for horizontal leaves when leaf reflectance and transmittance factors are the same (Goudriaan, 1977). However, in the low leaf reflectance and transmittance wavebands, this approach produces a fairly good approximation.
When we assume the isotropic diffuse sky radiation, $K_{de}$ is given by Goudriaan (1977):

$$K_{de} = -\frac{\ln \left(2 \int_0^{\pi/2} \exp \left(-\sqrt{\tilde{g} G(\theta) L} \cos \theta \right) \sin \theta \cos \theta d\theta \right)}{L_{2,\text{mean}}}$$

(19)

It should be noted that the actual diffuse sky radiation is not isotropic. Especially on sunny days, strong diffuse sky radiation originates from near the solar disk (Hutchison et al., 1980). We treated the circum-solar diffuse radiation as a beam because in the actual beam fraction measurements that are proposed (Section 2.5.1.2), we used a finite-sized black paddle to obstruct not only the beam but also some of the circum-solar diffuse radiation. Diffuse illumination at the canopy depth $L$ is:

$$I_{\text{diff}}(L, \theta_s) = F_{\text{fotf}} T_d(L) + F_{\text{fotbm}} \exp(-\sqrt{\tilde{g} K_{de}(\theta_s) L}) - \exp(-K_{de}(\theta_s) \Omega_L(L))$$

(20)

When the forest floor is covered by snow and $L$ is low, such as in spring and autumn in boreal and temperate forests, radiation that is reflected off the surface snow and then scattered by leaves is not negligible (Kobayashi and Iwabuchi, 2008; Pinty et al., 2011). Incident irradiance at the canopy floor is:

$$I_L = F_{\text{fotf}} T_b(\theta_s, L) + F_{\text{fotbm}} T_d(Lc)$$

(21)

A flat snow surface can have a strong specular reflectance (Peltoniemi et al., 2005). However, due to large-scale roughness of the snow cover, caused by microtopography and heterogeneous snow thaw, the directional reflectance of snow is complex. Because we modeled the diffuse radiation field being isotropic, we only considered the directionality of reflectance as a function of the incident beam angle. If the reflectance at the surface below the canopy is $R_b(\theta_s, \phi_s)$ for the beam (black sky albedo) and $R_{bp}(\theta_s, \phi_s)$ for the diffuse (white sky albedo) portions, the illumination contribution from reflected radiation from the soil surface to the canopy at depth $L$ is:

$$I_{\text{refl}}(L) = \left(\frac{R_b}{\pi} F_{\text{fotf}} T_b(\theta_s, L) + \frac{R_{bp}}{\pi} F_{\text{fotbm}} T_d(Lc)\right) \exp(-\sqrt{\tilde{g}} \Omega_{\text{de}}(Lc - L)).$$

(22)

Equation (20) can be rewritten as

$$I_{\text{diff}}(L, \theta_s) = F_{\text{fotf}} T_d + F_{\text{fotbm}} \exp(-\sqrt{\tilde{g} K_{de}(\theta_s) L}) - \exp(-K_{de}(\theta_s) \Omega_L(L)) + I_{\text{refl}}(L).$$

(23)

For diffuse radiation, the scattering transfer function can be computed by the spherical integration of the scattering transfer function of beam. However, the equation contains a quadruple integral and is cumbersome to invert. The scattering transfer function can be approximated by a simpler equation (Norman and Jarvis, 1975):

$$F_{\text{diff}} = \frac{1}{\pi} \int_0^\frac{\pi}{2} \left\{ \frac{R_{dL} + R_{dR}}{2} (1 - \cos \alpha) + \frac{T_{dL} + T_{dR}}{2} (1 + \cos \alpha) \right\} g(\alpha) d\alpha.$$

(24)

Strictly speaking, the scattering transfer function for diffuse radiation ($F_{\text{diff}}$) depends on the sensor’s view angle ($\theta_v$); however, we ignored this effect in equation (24) because this effect is much weaker than the view angle dependency of the beam scattering phase function. Finally, the scattered radiation from the diffuse sky and intra-canopy scattering components is:

$$dI_{\text{diff}} = I_{\text{diff}} F_{\text{diff}} e^{-\Omega_{\text{de}}(\theta_v)(Lc - L)/\cos \theta_v} dL$$

(25)

Here, we use the same attenuation factor, $e^{-<\Omega_{\text{de}}(\theta_v)(Lc - L)/\cos \theta_v}$, that we used for the beam component (equation (11)).

2.1.4. Total scattering from plant canopies

The scattered radiation from leaves that extends to the sensor at the bottom of the canopy can be written as the sum of the beam and diffuse components:

$$I_1(\theta_v, \theta_s) = \int_0^{Lc} (dI_{\text{bn}} + dI_{\text{diff}})dL$$

(26)

Equation (26) is an integral of incoming radiation over the vertical leaf area profile ($L$).

2.1.5. Incoming diffuse sky radiation

To compute the scattering factor ($S$) in equation (2), we need diffuse sky radiation measurements ($I_{\text{sky}}$) of the radiation originating from the portion of the sky that is viewed by a particular ring of the LAI-2200. $I_{\text{sky}}(\theta_v, \theta_s, \phi_s)$ is calculated as follows:

$$I_{\text{sky}}(\theta_v, \theta_s, \phi_s) = \frac{\phi_{\text{vnc}}(\theta_v, \theta_s)}{\pi} \int_0^{\pi/2} \int_0^{2\pi} \frac{O_{\text{vnc}}(\theta_v, \theta_s) \cos \theta_v d\theta_v d\phi_v}{2}$$

(27)

where $O_{\text{vnc}}(\theta_v, \theta_s)$ and $\phi_{\text{vnc}}(\theta_v, \theta_s)$ are the sky radiation measurements by an LAI-2200 with a narrow view cap (e.g., 45° field of view) and a wide view cap, respectively, and $\phi_{\text{vnc}}$ and $\phi_{\text{vnc}}$ are azimuth angles for the narrow and wide view caps, respectively. The inverses of $\phi_{\text{vnc}}$ and $\phi_{\text{vnc}}$ are multiplied in equation (27) to account for the area that the sensor views. For $O_{\text{vnc}}(\theta_v, \theta_s)$, a 360° field of view would be ideal, but when the sun is not obscured, a field of view of about 270–315° can be a practical limit. $I_{\text{sky}}$ will be equal to $F_{\text{diff}} F_{\text{tot}}$ when the sky is isotropic.

2.2. Inversion scheme

$L$ and the clumping index are estimated from measured gap fraction data. We took a physically based approach through the inversion of the simple bidirectional transmission model. For the leaf angle distribution function, $g(\alpha)$, we used a single parameter ellipsoidal leaf angle distribution function (Campbell, 1986, 1990) because of its simplicity. The inversion of the simple bidirectional transmission model includes three unknown factors: total LAI ($L_c$), the clumping index at the view zenith angle ($\Omega(\theta_v)$), and the leaf angle parameter for the ellipsoidal leaf angle distribution ($x$). We used the previously proposed inversion scheme (Norman and Campbell, 1989). An initial estimate of $L_c$ is determined by Miller’s theorem (Miller, 1967; Welles and Norman, 1991):

$$L_{\text{eff}} = -2 \int_0^{\pi/2} \ln(\rho_{\text{vnl}}(\theta_v)) \cos \theta_v \sin \theta_v d\theta_v.$$

(28)

where $L_{\text{eff}}$ is effective LAI. The over bar of $\rho_{\text{vnl}}(\theta_v)$ is the mean of all gap fraction measurements at the study site (Ryu et al., 2010a). True $L_c$ can be derived by the following equation:

$$L_c = \frac{L_{\text{eff}}}{\Sigma_{\text{mean}}}. $$

(29)

Through estimation of $L_c$, the radiation at zenith (or nadir) is calculated as

$$\Omega(\theta_v) = \frac{\Omega_{\text{de}}(\theta_v)}{\cos \theta_v},$$

(30)

where $\Omega_{\text{de}}(\theta_v)$ is the ratio of the logarithm of the mean gap fraction divided by the mean of the logarithms of the gap fractions (Lang and Xiang, 1986; Ryu et al., 2010a,b). The scattering factor ($S$) in equation (2) is determined from the initial estimates of $L_c$ and $\Omega(\theta_v)$, which are computed using
Once $S$ is obtained, the true gap fractions $P_0(\theta_e)$ are computed by subtracting $S$ from $P_{0m}(\theta_e)$. $\boldsymbol{\Omega}(\theta_e)$ is updated with the method of Lang and Xiang (1986) and Ryu et al. (2010a). As was described in Norman and Campbell (1989), the solution of $L_e$ and $x$ can be found using a nonlinear least square analysis with the constraint of $x \times 0$. The evaluation function that should be minimized is given by:

$$\psi = \sum (\ln P_0(\theta_e) + K_{\text{rec}}(\theta_e, x) \Omega(\theta_e) L_e)^2. \quad (30)$$

The minimum of $\psi$ can be found by solving $\partial \psi / \partial x = 0$ and $\partial \psi / \partial \theta = 0$. Inversion of the bidirectional transmission model requires leaf reflectance ($R_{LD}$, $R_{LS}$) and transmittance ($T_{LD}$) factors, and the fraction of incoming diffuse radiation ($f_{\text{dd}}$) all in the appropriate wavelength band of the LAI-2200. These quantities are input measurements that are needed for the inversion.

2.3. Model evaluation with a 3D bidirectional transmittance model

We performed a model evaluation at four different sites: an oak-grass savanna woodland in California, and in a birch stand, a pine stand, and a spruce stand in the Järveja Training and Experimental Forestry District, Estonia. In the oak-grass savanna woodland, we conducted field surveys and collected most of the data for the model run. At the three Järveja sites, we used data that were collected by Kuusk et al. (2009). Detailed descriptions of the field data are provided in Section 2.5.

To determine how well the proposed simple bidirectional transmission model performs in heterogeneous plant canopies, we compared the simple model to a 3D radiative transfer model, the Forest Light Environmental Simulator (FLIES) (Kobayashi et al., 2012; Kobayashi and Iwabuchi, 2008). FLIES simulates the light environments in 3D plant canopies based on a Monte Carlo ray-tracing approach. This approach can simulate higher-order scattering interactions with individual crowns and woody elements. This model calculates bidirectional reflectance using the local estimation method, in which the top of the canopy radiation contribution at each scattering event is sampled for every scattering event. The same analogy was applied to computation of scattered radiation ($I_s$); we used the local estimation method and sampled the bottom canopy scattering radiation contributions at every scattering event while performing Monte Carlo ray-tracing within the canopy. Specular reflectance from the leaf surfaces was also considered using the formula from Section 2.1.2. FLIES has an atmospheric radiative transfer module (Kobayashi and Iwabuchi, 2008; Ryu et al., 2011) and can simulate the angular distribution of incoming diffuse radiation. FLIES was used in a radiation model inter-comparison study (RAMI4PILPS), and it was confirmed that the model performs fairly well in a wide variety of landscapes, from simple homogeneous turbid media to highly heterogeneous open canopies (Widowski et al., 2011). The simple model and FLIES were compared using a heterogeneous plant canopy described in Section 2.5.1. For the FLIES run, we created a landscape based on the airborne LiDAR observations in an oak-grass savanna site and tree census data from the three other sites. We used a 100 × 100 m landscape unit repeatedly so that a horizontally infinite landscape was obtained. Therefore, there were no edge effects (size effects) in the simulation. Tree positions and their crown diameters were extracted using the LiDAR-based automated tree extraction algorithm (Chen et al., 2006). We modeled individual crowns using spheroid shapes with two domains; outer and inner domains were occupied by randomly distributed leaves and woody elements. Heights and diameters of inner domains were set to 70% of crown dimensions. We assumed constant leaf and woody area densities ($m^2 \cdot m^{-3}$) over all of the crowns. Stems were modeled as cylinders.

We simulated the scattering factor ($S$) at two different solar zenith angles ($\theta_s = 27^\circ$ and $80^\circ$), and five view zenith angles ($\theta_v = 7^\circ$, $22^\circ$, $37^\circ$, $53^\circ$ and $67^\circ$), which correspond to the centers of the five rings in the LAI-2200 optical sensor, and two relative azimuth angles ($\phi_v = 90^\circ$ and $180^\circ$). The simulation of $S$ in equation (2) was done using an $L_e$ of 0.85 and a woody area index of 0.35, which were close to the measured values (Kobayashi et al., 2012; Ryu et al., 2010a). We used an electrophilic leaf angle distribution with a mean leaf inclination angle of $62^\circ$, based on in situ measurements (Ryu et al., 2010b).

2.4. Atmospheric radiative transfer simulation

We used FLIES to evaluate the angular variability of the sky radiation ($I_{\text{sky}}$). Sky radiation was calculated using the following conditions: average continental aerosol (defined by Hess et al., 1998), aerosol optical thickness of 0.1 at 550 nm, and an atmospheric profile of mid-latitude summer as defined in LOWTRAN (Kneizys et al., 1988). Here, we assumed clear skies only because broken cloud conditions are challenging, both for simulating sky radiation and estimating $L_e$ and $\boldsymbol{\Omega}(\theta)$.

2.5. Field data

2.5.1. Oak-grass savanna site

The study site was classified as an oak-grass savanna ecosystem in central California, USA (Tonzi Ranch: latitude: 38.4311° N; longitude: 120.9508° W; altitude: 177 m). The site is located in the foothills of the Sierra Nevada Mountains and it experiences a Mediterranean type climate with dry, hot summers and rainy, mild winters. Annual average temperature and annual total precipitation were 16.9 °C and 565 mm yr$^{-1}$, respectively (1949–2005 climate normals from Camp Pardee climate station; latitude: 38.258° N; longitude: 120.858° W). The overstory was dominated by blue oak trees (Quercus douglasii) with occasional (<10%) gray pine trees (Pinus sabiniana) (Ryu et al., 2010b). The understory is mainly composed of grasses and forbs (Brachypodium distachyon, Hypochaeris glabra, Bromus madritensis, Cynodon echinatus). Leaf and woody area indices are 0.82 ± 0.22 (by litterfall collection) and 0.32 ± 0.08 (by digital camera), respectively, and the best estimate of the clumping index was 0.49 ± 0.10 (Ryu et al., 2010b). Stem density was 144 ha$^{-1}$, tree height was 9.4 ± 4.3 m (mean ± standard deviation), trunk height was 1.8 ± 1.3 m, diameter at breast height (DBH) was 0.26 ± 0.11 m, mean crown radius was 2.9 ± 1.4 m, and canopy cover was 0.47, leaf scattering coefficient for the blue band (450 nm) for blue oak was 0.085 (Kobayashi et al., 2012).

2.5.1.1. Gap fraction from LAI-2200 sensors. To characterize the impact of scattered radiation from the canopy on the gap fraction measurements, we collected gap fraction data on 27 July 2010 and 3 Aug 2010, two cloudless days. The gap fraction was measured across three parallel north-to-south transects. Each transect was 300 m long and measurements were taken at 30 m intervals ($N = 33$), which was three times the mean canopy height, or roughly the footprint of the LAI-2200 sensor. A 23 m tall flux tower was located at the center of the three transects. Two LAI-2000 sensors were located at the top of the flux tower to measure reference incoming light intensity and two LAI-2200 sensors provided incoming light intensity data below the canopy along the transects. Each pair of LAI-2200 or LAI-2000 sensors was matched by placing both sensors at the top of the tower before taking the transect measurements. A 45° field of view cap was used in this study. The azimuthal orientations of the pairs of LAI-2200 and LAI-2000 sensors were different. One pair always had an azimuthal orientation that was perpendicular to the direction of the sun (solar azimuth ±90°), and the other pair viewed at either ±135° or 180° from the...
solar azimuth (Table 1). Hemispherical sky light intensity, $I \left( \theta_s, \phi_s \right)$, in equation (27), was measured using a 270° field of view cap at the top of the tower before and after the three transect measurements; the view cap orientation was adjusted to block the direct solar beam.

2.5.1.2. Fraction of diffused blue radiation. The ratio of incoming diffused blue radiation (320–490 nm) to total incoming blue radiation ($I_{BL}$) was quantified at an open location at the site. A view cap that had a small hole (1.27 mm in diameter) at the center was attached to an LI-2200 instrument. The field of view with this view cap was 4° (half angle) for a 50% response, and 7° (half angle) for a 90% response. The LI-2200 sensor pointed in the nadir direction above a white Halon diffuse reflectance standard panel (99% reflectivity, 25 cm × 25 cm, Spectralon, Labsphere Inc.). The LI-2200 sensor measured the light reflected by the white panel, which indicated incoming blue radiation. Then, using a 3 m handle, a black paddle that was twice the size of the white standard panel was positioned between the sun and the white standard panel to cast a shadow on the white standard panel. The shadow was twice the size of the white standard panel to ensure that the penumbra of the shadow did not fall on the white standard panel. The fraction of diffuse blue radiation was calculated by dividing the shaded reading by the unshaded readings using ring 1 of LI-2200.

2.5.1.3. Leaf optical properties. We used LI-2200 with the 1.27 mm hole view cap to measure leaf transmittance ($T_{DL}$) and reflectance ($R_{DL}$) factors. The LI-2200 over the white standard panel measured incoming blue radiation. We put leaves on the white standard panel, placed the LI-2200 over about 20 cm above the leaves, and collected the reflected light by the leaves. The ratio of the reflected light by the leaves to the reflected light by the white standard panel provided the leaf reflectance factor. For transmittance measurements, we attached a leaf on the sensor’s view cap to make sure that the 1.27 mm hole view cap was covered by the leaf. The leaf transmittance was computed as a ratio of the light transmitted through the leaf and the direct light from the white standard panel. We did this process for five leaves, and determined the reflectance and transmittance factors of the leaves for the blue radiation to be $5.35 \pm 0.49\%$ and $1.28 \pm 0.26\%$, respectively (Table 2). The reflectance factors we measured are close to the independent measurement by a spectrometer (USB2000, Ocean Optics Inc.) at the same site ($6.27\%$ at 380–490 nm) (Chen et al., 2008).

2.5.2. Järvesjelä sites

The comparison between the proposed simple scattering model and the 3D model (FLiES) was repeated in three different forest types (birch (Betula pendula, Betula pubescens), pine (Pinus sylvestris), and spruce (Picea abies) stands) located at the Järvesjelä Training and Experimental Forestry District, Estonia (latitude: 27.268°E; longitude: 58.324°N). Forest census data were collected by the Tartu Observatory during a radiative transfer model validation study (Kuusk et al., 2009). We used data on 100 × 100 m tree horizontal positions, tree heights, crown diameters, crown vertical lengths, and leaf and stem reflectance and transmittance factors ($R_{DL}$, $T_{DL}$, and $R_{stem}$). Table 2 summarizes the forest characteristics. For the birch stand, birch (Betula) was the dominant species, but other species made up about 50% of the population (Tilia cordata, Alnus glutinosa, and Populus tremula). For the spruce stand, spruce was the dominant species, but birch made up 17% of the tree population. The leaf and stem optical properties shown in Table 2 are weighted average for these species. The $I_C$ values are allometry-based values. The element clumping index at each site was computed as the ratio of $L_{f}\text{Tot}$ to $L_{c}$. For needle stands (pine and spruce), we assumed that shoot-level clumping was $\gamma = 1.4$ (Chen et al., 1997). The clumping index $\Omega$ was computed as $\Omega = \Omega_{tot}/\gamma$. $R_{DL}$ and $T_{DL}$ for the simple model were the weighted averages of leaf and stem reflectance and transmittance factors, respectively. Because the simple model does not distinguish between woody parts and leaves, we used weighted average values as inputs. We compared the models under two different solar zenith angles (35° and 80°) and azimuth angles (90° and 180°), which correspond to noon-time in summer and near sunset. Unlike the oak-grass woodland site, no information was available about the fraction of diffuse radiation. We used diffuse sky measurements ($I_{diff}$, $O_{oec}(\theta_s, \phi_s)$ and $O_{oec}(\theta_s, \phi_s)$) at the oak-grass woodland site (solar zenith angles of 25° and 80°) for the three Järvesjelä sites (solar zenith angles of 35° and 80°).

3. Results

3.1. Simulated incoming diffuse sky radiation

The stronger the incoming diffuse sky radiation, the smaller the impact of the scattering factor in equation (2), because $I_{sky}$ is found in the denominator of this equation. It is important to consider the general patterns in the angular variability of $I_{sky}$. Fig. 2 shows the simulated angular distribution of the sky radiation ($I_{sky}/I_{diff\text{Tot}}$) for
Table 2
Summary of the forest sites. Leaf and stem optical data are the weighting average of all existing species. LAI: leaf area index, WAI: woody area index, \( R_{DL} \) (SM): weighted average of leaf and stem transmittance for the proposed simple model input, \( T_DL \) (SM): weighted average of leaf and stem reflectance for the proposed simple model input.

<table>
<thead>
<tr>
<th>Site</th>
<th>Species (# tree %)</th>
<th>Tree density (ha(^{-1}))</th>
<th>LAI</th>
<th>WAI</th>
<th>( \text{LAI}_{\text{eff}} )</th>
<th>( \Omega )</th>
<th>( R_{DL} )</th>
<th>( T_{DL} )</th>
<th>( R_{sm} )</th>
<th>( R_{DL} ) (SM)</th>
<th>( T_{DL} ) (SM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>US-Tonzi (38.4311'N, 120.9508'W)</td>
<td>Q. douglasii (&gt;90%)</td>
<td>139</td>
<td>0.8</td>
<td>0.4</td>
<td>-</td>
<td>0.5</td>
<td>0.0535</td>
<td>0.0328</td>
<td>0.133</td>
<td>0.0723</td>
<td>0.0083</td>
</tr>
<tr>
<td>Järvselja-birch (58.2805'N, 27.3310'E)</td>
<td>B. pendula (50%), T. cordata (20%), A. glutinosa (19%), P. tremula (8%)</td>
<td>1031</td>
<td>3.93</td>
<td>2.37</td>
<td>2.94</td>
<td>0.75</td>
<td>0.0644</td>
<td>0.0086</td>
<td>0.22</td>
<td>0.0888</td>
<td>0.0073</td>
</tr>
<tr>
<td>Järvselja-pine (58.3114 N, 27.2968'E)</td>
<td>P. sylvestris (99%)</td>
<td>1121</td>
<td>1.86</td>
<td>0.65</td>
<td>1.75</td>
<td>0.67</td>
<td>0.058</td>
<td>0.0019</td>
<td>0.084</td>
<td>0.0054</td>
<td>0.0074</td>
</tr>
<tr>
<td>Järvselja-spruce (58.2956'N, 27.2561'E)</td>
<td>Picea abies (82%), Betula (17%)</td>
<td>1689</td>
<td>4.36</td>
<td>1.5</td>
<td>3.76</td>
<td>0.62</td>
<td>0.034</td>
<td>0.0009</td>
<td>0.158</td>
<td>0.0051</td>
<td>0.0073</td>
</tr>
</tbody>
</table>

\( \theta_s = 30^\circ \) and \( 60^\circ \) using the atmospheric radiative transfer model in FLiES (see Section 2.4). Three different sensor view azimuth angles (\( \varphi_v = 20^\circ \), \( 90^\circ \), and \( 180^\circ \)) are shown. The sun azimuth direction is \( \varphi_v = 0^\circ \), therefore, \( \varphi_v = 20^\circ \) is the closest to the sun. \( I_{sky} \) increases as the sensor view zenith angle gets closer to the sun. This is because atmospheric aerosols have strong forward scattering properties. When \( \varphi_v = 20^\circ \), the diffuse sky radiation flux density approaches its maximum near the sun direction. When \( \varphi_v = 90^\circ \) and \( 180^\circ \), the view-zenith-angular variation in \( I_{sky} \) is weaker than with \( \varphi_v = 20^\circ \). \( I_{sky} \) when \( \varphi_v = 90^\circ \) is slightly higher than when \( \varphi_v = 180^\circ \) because it is closer to the sun.

### 3.2. Sensitivity of the scattering factor to canopy structure and sky condition

Using the proposed model, we simulated scattering factors and gap fractions under various \( L_c \) and clumping conditions. The impact of the scattering factor, \( S \), on the gap fraction, \( P_{0,m} \), depends on \( L_c \), \( \Omega \), and the sky conditions (Fig. 3). \( S \) peaks at \( L_c = 1–2 \). When \( L_c \) drops below 1, \( S \) decreases abruptly due to a reduction in the scattering media (leaves). As \( L_c \) increases above 2, \( S \) also decreases because most of the scattering occurs in the upper layer of the canopy and is intercepted by leaves before the scattered radiation reaches the LAI-2200 sensor that is lower in the canopy. In cases with lower solar zenith angles (Fig. 3a and b), the scattering factor is largest with a view angle of \( 67^\circ \) because the sensors detect a larger fraction of the leaf elements form an oblique angle. With lower view angles, where Fresnel reflection is highest, the contribution of specular view angle is overwhelming. Thus, the scattering factor with a view angle of \( 7^\circ \) is higher than with a view angle of \( 22^\circ \) or \( 37^\circ \).

Scattering effects are dependent on the solar zenith angle (\( \theta_s \)); higher sun zenith angles with higher diffuse fractions have less scattering and thus smaller errors in gap fraction estimates (Fig. 3). Scattering radiation that passes through the canopy layer and reaches the bottom of the canopy has a strong vertical dependency that is associated with solar and view zenith angles, and the fraction of diffuse radiation (Fig. 4). When the solar zenith angle is low (Fig. 4a), scattering radiation from the lower canopy becomes stronger as the view zenith angle increases. On the other hand, when the solar zenith angle is high (Fig. 4b), scattering radiation from the upper canopy becomes stronger as the view zenith angle decreases. These changes in the vertical profile occur with changes in the plant canopy path lengths for solar beam and scattered radiation. Clumped canopies (\( \Omega = 0.6 \)) reduce the scattering effect because more light penetrates without scattering through than passing a random canopy (\( \Omega = 1.0 \)) and the clumps of vegetation have lower effective scattering coefficients. As a result, with clumping, the peak in \( S \) occurs at a higher \( L_c \) value (LAI = 2.0) compared to the case with a random canopy (LAI = 1.0). Although \( S \) was highest when \( L_c \) was between 1 and 2, the contribution of the scattering factor to the gap fraction did not coincide with the peak in \( S \) because \( P_{0,m} \) decreases with \( L_c \). Because gap fractions decrease exponentially with \( L_c \) (lower panels in Fig. 3), the scattering factor, \( S \), can be a substantial contributor to the gap fraction. To determine the LAI-equivalent error due to scattering, we calculated \( \Delta \text{LAI}_{\text{true}} = -\ln(P_{0,m}(\theta)/K_{\text{dl}}(\theta)\Omega) \) and \( \Delta \text{LAI}/\text{LAI}_{\text{true}} = (\text{LAI}_{\text{true}} - \text{LAI}_{\text{true}})/\text{LAI}_{\text{true}}, \) where \( P_{0,m} \) is the gap fraction with scattering and \( \text{LAI}_{\text{true}} \) is the true value of \( L_c \). Fig. 5 shows the simulated LAI-equivalent error from the simple model for five sensor view angles in the LAI-2200 rings. Under sunny conditions

![Fig. 2. Angular variability of normalized sky radance by the total diffuse radiation (\( I_{sky} \)) of the five LAI-2200 view zenith angles (\( \theta_s = 7^\circ, 22^\circ, 37^\circ, 53^\circ, \) and \( 67^\circ \)). (a) \( \theta_s = 30^\circ \) (b) \( \theta_s = 60^\circ \).](image-url)
Fig. 3. Simulated results of scattering factors (S) (upper figures) and uncorrected gap fraction (P0,m) (lower figures) by the simple model proposed in this study. View angles of 7, 22, 37, 53, and 67 are view zenith angle and correspond to the center of the five LAI-2200 rings. (a) θv = 27°, φv = 90°, fdisp = 0.25, Ω = 1.0, (b) θv = 27°, φv = 90°, fdisp = 0.25, Ω = 0.6, (c) θv = 80°, φv = 90°, fdisp = 0.85, Ω = 1.0, (d) θv = 80°, φv = 90°, fdisp = 0.85, Ω = 0.6. Other parameters are spherical leaf angle distribution (x = 1.0), leaf diffuse reflectance (RDL = 0.0535), leaf transmittance (TDL = 0.0128), leaf hair index (k = 0.15), fraction of adaxial leaf specular contribution (fada = 0.5), and forest floor reflectance (Rfb = Rfw = 0.0). All symbols are defined in the Nomenclature.

Fig. 4. Simulated vertical profiles of relative scattering contribution (%) that penetrates plant canopy layer and reaches to the canopy floor. Cumulative LAI of 0 and 4 correspond to the top and bottom of the canopy layer. Total canopy LAI is 4.0. (a) θv = 27°, φv = 90°, fdisp = 0.25, Ω = 1.0, spherical leaf angle distribution is assumed. (b) θv = 80°, φv = 90°, fdisp = 0.85, Ω = 1.0. Other parameters are spherical leaf angle distribution (x = 1.0), leaf diffuse reflectance (RDL = 0.0535), leaf transmittance (TDL = 0.0128), empirical parameter for the specular reflectance correction factor (k = 0.15), fraction of adaxial leaf specular contribution (fada = 0.5), and forest floor reflectance (Rfb = Rfw = 0.0). All symbols are defined in the Nomenclature.
with low diffuse sky radiation, the error ($\delta$LAI/LAI_{true}) increases as $L_c$ increases. A sensor view zenith angle of 67°, which corresponds to the fifth ring of the LAI-2200, had the largest impact on the scattering effect. Under diffuse sky conditions, the error ($\delta$LAI/LAI_{true}) was usually less than 8%, except with a view zenith angle of 67°. Unlike the case with sunny conditions, lower values of $L_c$ tended to produce higher errors.

The scattering factor is enhanced when $S$ in equation (1) is computed with non-zero forest floor reflectance conditions. The forest floor reflectance contribution to equation (26) is a linear function of $R_{fw}$. Therefore, when assuming a Lambertian surface ($R_{fb} = R_{fw}$), we can rewrite the scattering factor as a function of $R_{fw}$:

$$S(\theta_v, \theta_S, \psi_r) = a(L)R_{fw} + S_{R_{fw}=0}(\theta_v, \theta_S, \psi_r)$$  \hspace{1cm} (31)

Here, $a(L)$ is a slope and $S_{R_{fw}=0}$ only contains scattered radiation from leaves. Larger values of $a(L)$ indicate a larger effect of forest floor reflectance. Fig. 6 shows the slope for five view angles as a function of $L_c$. In both clumped (Fig. 6a) and non-clumped (Fig. 6b) cases, the slopes were largest when $L_c$ was approximately 1, and the maximum $a$ for $L_c = 1$ was around 0.04 with a view angle of 67°. For example, when $R_{fb} = R_{fw} = 0.5$ and $\Omega = 1.0$, the first term of equation (31) becomes $a(L)R_{fw} = 0.02$ at $L_c = 1$. This is added to the scattering factor with a black forest floor ($S_{R_{fw}=0} = -0.04$) in Fig. 3a.

We compared the results of the simple model to those of FLiES to understand how the simple model performs in diverse ecosystems, with low to high values of $L_c$ (Table 2). The simulated scattering factor from our model agreed well with the FLiES results for the oak-grass savanna (root mean square error, RMSE = 0.0033 and mean bias = -0.0010), the Järvselja pine (RMSE = 0.0048 and mean bias = 0.0025), and the Järvselja spruce (RMSE = 0.0051 and mean bias = -0.0024) (Fig. 7a). However, in the Järvselja birch, the estimated scattering factor was much lower (RMSE = 0.013 and mean bias = -0.080) than the results from FLiES. This underestimation was substantial at an azimuth angle of 180°. This is because the stems were much brighter than the leaves in the birch stand and scattered radiation from stems dominated the result. As is shown in Fig. 4a, the relative scattering contribution from the lower level canopy was stronger when the sensors detected more stems than leaves. To determine if the effects of bright stems can be adjusted.
by simply changing the input leaf reflectance factor, we replaced the leaf diffuse reflectance factor \( R_{DL} \) by \( 0.0888 \) with the arithmetic average \( R_{DL} \) for birch stand = 0.143 \( \) (Fig. 7b). The adjusted leaf reflectance results produced a better relationship between the results of the two models (RMSE = 0.008 and mean bias = −0.0020). The results for the Järvselja spruce stand are also shown in Fig. 7b because this stand also contains 17% of birch trees. The adjusted leaf reflectance factor also produced better results (RSME = 0.0036 and mean bias = −0.0012).

3.3. Impact of scattering effects on LAI and clumping index estimates

We determined the extent to which scattering effects influenced estimates of \( L_c \) and the apparent clumping index using in situ LAI-2200 data (Table 1). Scattering effects caused significant underestimation of \( L_c \) (paired \( t \)-test, \( p < 0.05 \)) and significant overestimation of the apparent clumping index (paired \( t \)-test, \( p < 0.05 \)).

Overall, the \( L_c \) was underestimated by up to 26% under sunny conditions and 7.7% under diffuse sky conditions, and the apparent clumping index was overestimated by up to 14% under sunny condition and 4.3% under diffuse sky conditions. The relative difference in the azimuthal angle between the sensor view cap opening and the sun caused different scattering effects. Without the scattering correction, the \( L_c \) estimates at a relative azimuth angle of 90° was significantly higher than that estimate at 180° (paired \( t \)-test, \( p < 0.05 \)). With the scattering correction, there was no significant difference in \( L_c \) between the 180° azimuth difference and the differences of 90° or 135° (paired \( t \)-test, \( p > 0.05 \)). The dependency of estimated \( L_c \) on solar zenith angle was correctly eliminated and the standard deviation of the \( L_c \) estimates was reduced from 0.062 to 0.016 (Fig. 8a). With uncorrected \( L_c \) at a solar zenith angle of 61°, estimated \( L_c \) with a lower fraction of diffuse irradiance was lower, but after the correction, the difference disappeared (Fig. 8a). The apparent clumping index decreased after the correction for scattering radiance from leaves was applied, which is assumed to be...
black during computations of gap fractions (Fig. 8b). After the correction, solar zenith angle dependency of the apparent clumping index was eliminated. However, the estimated apparent clumping index (0.73) was about 30% higher than the best estimate of the clumping index (0.49) by Ryu et al. (2010b) because assumption of randomly distributed leaves in space within each ring’s footprint is violated due to large spatial heterogeneity in an oak-grass woodland (Ryu et al., 2010a).

4. Discussion

4.1. How can scattering effects be removed?

Scattering effects have been recognized and evaluated in some previous studies (Chen et al., 1997; Leblanc and Chen, 2001; Stenberg et al., 1994). Methods for removing scattering effects include removing the outer rings of the LAI-2200 instrument (Chen et al., 1997; Cutini et al., 1998) and applying an empirical function that depends on the solar zenith angle and effective $L_c$ measured under sunlit conditions (Leblanc and Chen, 2001). Our results showed that scattering effects appeared in all of the sensor rings (Figs. 3 and 4), therefore, removing the outer rings is unlikely to provide a good solution for removing scattering effects mechanistically. Also, removing the outer rings leads to the loss of gap fraction information from those rings. To better quantify canopy architecture, it is desirable to use gap fraction data from all of the rings. The gap fraction correction proposed here can be summarized in five steps.

Step 1: Measure the directional variation in sky radiation. Use a wide view cap (270° or wider) for incoming blue-band diffuse radiation and a narrow-view cap that has the same view angle for the gap fraction measurements under the canopy (e.g., 45°). The narrow-view cap measurement should be made in exactly the same azimuthal direction as the gap fraction measurement under the canopy.

Step 2: Measure the fraction of diffuse blue-band sky radiation. In this study, the fraction of diffuse sky radiation was measured using the reflected radiation from a Halon panel with and without a direct solar beam.

Step 3: Collect the gap fraction measurements under the canopy.

Steps 4 and 5: The same as steps 1 and 2 but repeated after step 3.

In addition to the above steps, measurements of leaf reflectance and transmittance, and stem reflectance (for tree species) factors are necessary. One can estimate average leaf reflectance factor in the simple model as the average of leaf and stem reflectance factors. If the forest floor is covered by snow, snow reflectance factor also needs to be included. These values can be measured in the field using an LAI-2200 with a white reference panel or a spectrometer. However, variation among plant species in green leaf reflectance and transmittance in the blue band is small. In the blue band, leaf reflectance factor (or the average of leaf and stem reflectance factor for tree species) ranges in between 0.05 and 0.08, and leaf transmittance is approximately 0.01. Therefore, if the stems are not very bright (typically <0.1), one can assume these values when estimating the gap fraction.

4.2. Which factors contribute to the scattering effects?

Stenberg et al. (1994) argued that large scattering errors can occur under sunny conditions when $L_c$ is low and a large proportion of the leaves that are detected by the sensor are sunlit. The scattering factors that were simulated in this study support this hypothesis: when $L_c$ was relatively low (1–2) the scattering factor was the highest (uppermost figures in Fig. 2). Savannas, grasslands, boreal forests, and deciduous forests experience these conditions immediately after the budburst. However, the predicted $L_c$ errors become larger with higher values of $L_c$ (Fig. 5). Thus, it is even more important to correct for scattering effects in situations with high $L_c$ values.

The scattering factor behaved nonlinearly with respect to several variables; it was dependent on sky condition (Fig. 2), canopy structural variables such as the clumping index (Fig. 3), and land surface reflectance (Fig. 6). In addition, it depended on not only the zenith angle but also the azimuth direction. Leblanc and Chen (2001) employed an empirical correction for scattering. However, physically based modeling of the scattering effect, including both zenith and azimuthal directions, is necessary when measuring the gap fraction within a narrow field of view. The scattering factor has azimuthal dependency because of the strong azimuthal dependency of incoming diffuse sky radiation ($f_{sky}$) (Hutchison et al., 1980).
(Fig. 2) and anisotropic leaf scattering properties. With a cloudless sky, the highest value of L_{sky} occurred towards the direction of the sun, and it moderated the scattering factor (5). On the other hand, the lowest value of L_{sky} was in the azimuth direction of 180° from the sun, and this increases the scattering factor.

The arrangement of leaves that has a leaf reflectance factor (0.05) that is much higher than the leaf transmittance (0.01) can create azimuthally anisotropic scattering even though the leaves are symmetrically distributed about the azimuth. Near the direction of the sun (\varphi_{v} = 0°), the radiation that is scattered (transmitted) by a sunlit leaf is minimal because of low leaf transmittance; however, when the sensor detects a sunlit leaf in the opposite direction from the sun (\varphi_{v} = 180°), the scattered (reflected) radiation is about five times larger than when \varphi_{v} = 0°. Because of these two effects (azimuthal distribution of L_{sky} and leaf scattering anisotropy), the scattering effect is largest when \varphi_{v} = 180°. Importantly, our inversion approach, which is based on the simple bidirectional transmission model, provided unbiased \hat{L}_{e} estimates under various sky and sensor view conditions (Table 1, Fig. 8).

Bright ground, such as snow and bright soil, can enhance the scattering factor via multiple scattering between the ground and leaves. A comparison between two clumping conditions (\Omega = 1.0 and 0.6) showed that both non-clumped and clumped canopies has non-negligible effect of forest floor reflectance factor.

The treatment of specular reflection is essential for correcting the scattering that is encountered during gap fraction measurements. The impact of specular reflection is largest at low view zenith angles (the first ring [7] of LAI-2200). The effect of specular reflectance depends on the structure of the plant canopy. For most tree species, the adaxial side of their leaves is not as flat as the abaxial side because of the presence of rived veins. For simulations of bidirectional reflectance, it is not important to consider the leaf side because most of the specular reflectance occurs on the abaxial side. However, in simulations of bidirectional transmission, it is essential to appropriately consider the leaf side in specular reflection because the sensor measures a lot of scattered radiation from the adaxial sides of leaves, depending on the leaf angle distribution function. To date, very few modeling studies have examined the exact specular reflectance of the leaf surface. Therefore, we took a simple approach by improving existing specular modeling (equation (16)). The relative contribution from the adaxial side can be modified by changing the contribution factor in equation (16). For example, most crops, such as corn and rice, do not show distinct differences in leaf structure between adaxial and abaxial surfaces. Therefore, one can assume equal specular reflectance contributions from both sides of their leaves.

The scattering factors that were computed by the 1D and 3D models (the proposed simple model and FLIES) agreed across diverse ecosystems, from a low L_{e} of 0.82 (PAI = 1.20) to a high L_{e} of 4.36 (PAI = 5.86), and in both broadleaf and needleleaf forests (Fig. 7). One exception was a birch stand in which the stems were highly reflective. In this comparison, leaf reflectance factor was adjusted to be a weighted average of leaf and stem reflectance factor. Therefore, if the stems are not highly reflective (<0.12), our general assumption hold true. For the birch stand, leaf reflectance factor needed to be adjusted based on the vertical contribution to the scattering effect (Fig. 4a), because the lower canopy layer, where the stems were dominant, tends to contribute more to scattering more than the upper layer.

Lastly, to avoid creating biased estimates of L_{e} (underestimates) due to sky conditions and sun and view angle geometries, we recommend correcting for scattering effects under all observational conditions. Field data collected near sunset (1830 h, solar zenith angle = 84°) were consistently lower than the \hat{L}_{e} estimates after the correction (Table 1). This indicates that the correction for scattering effects is desirable even at dawn and dusk, unless the solar disk is below the horizon, which would constrain direct measurements to a very short period.

5. Conclusions

We show the effect of leaf scattering on gap fraction measurements and how this effect can be removed. This semi-physically based inversion approach provides more reliable gap fraction estimation than that of empirical methods. On the other hand, this new approach requires several simultaneous measurements such as directional variation of sky radiation, fraction of diffuse to total blue sky radiation, leaf reflectance and transmittance, and stem reflectance factors for tree species. In gap fraction measurements, one can choose the best experimental setup based on the accuracy required; if up to 26% underestimation is acceptable, Welles and Norman (1991)'s approach may be good enough. If one is only interested in measuring effective LAI, applying the empirical correction proposed by Leblanc and Chen (2001) with a wider field of view cap could be good enough. Finally, our inversion approach provides an opportunity to measure gap fractions and evaluate LAI and the apparent clumping index even in sunny conditions without biases (Fig. 8). This is especially useful in heterogeneous landscapes that require large numbers of samples that cannot be done in a short time periods at sunrise and sunset.

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