Agricultural and Forest Meteorology 174–175 (2013) 170–183

Contents lists available at SciVerse ScienceDirect

Agricultural and Forest Meteorology

journal homepage: sevier.com/locate/agrformet

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

Hideki Kobayashi[a,c], Youngryel Ryu[b,c,*], Dennis D. Baldocchi[c], Jon M. Welles[d], John M. Norman[e]

[a] Research Institute for Global Change, Japan Agency for Marine-Earth Science and Technology, Japan
[b] Department of Landscape Architecture and Rural Systems Engineering, Seoul National University, Republic of Korea
[c] Department of Environmental Science, Policy and Management, UC Berkeley, Berkeley, CA, USA
[d] LI-COR Biosciences, Lincoln, NE, USA
[e] Department of Soil Science, University of Wisconsin-Madison, Madison, WI, USA

a r t i c l e i n f o

Article history:
Received 18 April 2012
Received in revised form
10 December 2012
Accepted 19 February 2013

:
LAI-2000
LAI-2200
Gap fraction
Leaf area index
Clumping index
Scattering

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 radiance under a variety of ecosystem conditions, we compared simulated scattered radiance 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 m^2 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 woodland, 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) (Nilson, 1971; Ross, 1981; Ryu et al., 2012; Welles and Norman, 1991), apparent clumping index (Ryu et al., 2010a), 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 (Acock 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).

* Corresponding author at: Department of Landscape Architecture and Rural Systems Engineering, Seoul National University, Seoul 151-921, Republic of Korea. Tel.: +82 2 880 4871; fax: +82 2 873 5113.
E-mail address: yryu@snu.ac.kr (Y. Ryu).

0168-1923/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.agrformet.2013.02.013

Nomenclature

	zenith angle of a leaf surface normal direction
$_0$	angle between the sun and leaf normal
	azimuth angle of a leaf surface normal direction
	shoot clumping
	scattering transfer function
$_{bm}$	scattering transfer function for beam (= $_D$ + $_{SP}$)
$_D$	scattering transfer function, diffuse scattering of beam on leaf surface
$_{SP}$	scattering transfer function, specular reflectance of beam on leaf surface
$_{dif}$	scattering transfer function for diffuse radiation
	evaluation function for inversion
	leaf absorptivity
	plant canopy optical thickness
$_s$	solar zenith angle (0 <= $_s$ < 90 degree)
$_v$	view zenith angle (0 <= $_v$ < 90 degree)
ϕ_{nvc}	Azimuth angle of opening in LAI-2200 with a narrow view cap
ϕ_{wvc}	Azimuth angle of opening in LAI-2200 with a wide view cap
ϕ_r	relative view azimuth to solar azimuth angle
ϕ_s	solar azimuth angle
ϕ_v	view azimuth angle
ω	single scattering albedo (= $R_{LD} + R_{LS} + T_{LD}$)
( )	clumping index at
$_{mean}$	mean clumping index over the solar zenith angle $_s$
$a(L)$	constant for forest floor reflectance
f	correction factor of Fresnel reflectance
f_{ada}	correction factor of adaxial leaves
f_{bm}	fraction of beam incident radiation above canopy
f_{dif}	fraction of diffuse incident radiation above canopy
$F(,\phi, ,)$	fraction of leaf area with a leaf normal of (,)
F_{bm}	above-canopy beam irradiance perpendicular to the sun direction (W m^{-2})
F_{tot}	total incident solar irradiance perpendicular to horizontal plane (W m^{-2})
$g( )$	leaf angle distribution function
$G( )$	fraction of projected leaf area perpendicular to direction, G-function
h	canopy height
I_{dif}	incident diffuse radiance integrated over the upper hemisphere (W m^{-2})
I_f	incident radiance at canopy floor integrated over the upper hemisphere (W m^{-2})
$I_l(_s, _v,\phi_r)$	scattered radiance (W m^{-2} str^{-1})
$I_{lb}(_s, _v,\phi_r)$	scattered radiance of beam (W m^{-2} str^{-1})
$I_{ld}(_s, _v,\phi_r)$	scattered radiance of diffuse (W m^{-2} str^{-1})
I_{refl}	reflected radiance from the forest floor (W m^{-2} str^{-1})
$I_{sky}(_s, _v,\phi_r)$	diffuse sky radiance (W m^{-2} str^{-1})
k	empirical parameter for the specular reflectance correction factor f
$K_{be}(_s)$	beam extinction coefficient (=G($_s$)/cos $_s$)
K_{de}	extinction coefficient for diffuse radiation
L	LAI at the arbitrary height in plant canopy
L_c	total canopy LAI
L_{eff}	effective LAI
n	leaf surface refractive index
$O_{nvc}(_s, _v,\phi_r)$	sky radiance measured by LAI-2200 with a narrow view cap
$O_{wvc}(_s, _v,\phi_r)$	sky radiance measured by LAI-2200 with a wide view cap
$P(_s,\phi_s, _v,\phi_v)$	scattering phase function
$P_0(_s, _v,\phi_r)$	true gap fraction
$P_{0,m}(_s, _v,\phi_r)$	measured gap fraction (including a scattered radiation)
r_{sp}	Fresnel reflectance (average of the parallel and perpendicular polarized radiation)
R_{fb}	forest floor black sky albedo
R_{fw}	forest floor white sky albedo
R_{LD}	leaf diffuse reflectance factor
R_{LS}	leaf specular reflectance factor
R_{stem}	stem reflectance factor
$S(_s, _v,\phi_r)$	scattering factor
$S_{R_{fw}=0}$	scattering factor of a black forest floor condition
$T_d(L)$	diffuse transmittance
T_{LD}	leaf transmittance factor
u	leaf area density (m^2 m^{-3})
v	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 hemispheric 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 diffuse 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 $P_{0,\text{mes}}$ can be written as:

$$P_{0,\text{m}}(\theta_s, \theta_v, \phi_r) = P_0(\theta_v, \phi_v) + S(\theta_s, \theta_v, \phi_r) \tag{1}$$

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

$$S(\theta_s, \theta_v, \phi_r) = \frac{I_l(\theta_s, \theta_v, \phi_r)}{I_{\text{sky}}(\theta_s, \theta_v, \phi_r)} \tag{2}$$

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

$$P_0(\theta_v, \phi_v) = P_{0,\text{m}}(\theta_s, \theta_v, \phi_r) - \frac{I_l(\theta_s, \theta_v, \phi_r)}{I_{\text{sky}}(\theta_s, \theta_v, \phi_r)} \tag{3}$$

2.1. Simple invertible bidirectional transmission model

To estimate LAI from $P_{0,\text{m}}$, 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 Ω (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 $P_{0,\text{m}}$, 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:

$$\cos\theta_v \frac{dI}{d\tau} = -I + \frac{\omega}{4\pi} P(\theta_s, \phi_s, \theta_v, \phi_v) F_{\text{bm}} e^{-\tau/\cos\theta_s}, \tag{4}$$

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

$$\tau = \int_0^h u\,\Omega(\theta)G(\theta)dz = L\,\Omega(\theta)G(\theta), \tag{5}$$

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 (θ) and is called the G-function, $\Omega(\theta)$ is the clumping index. The derivative form of equation (5) is:

$$d\tau = \Omega(\theta)G(\theta)dL \tag{6}$$

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

$$\cos\theta_v \frac{dI}{\Omega(\theta_v)G(\theta_v)dL} = -I + \frac{F_{\text{tot}} f_{\text{bm}} \omega}{4\pi \cos\theta_s} P(\theta_s, \phi_s, \theta_v, \phi_v)\, \Omega(\theta_s) e^{-\Omega(\theta_s)G(\theta_s)L/\cos\theta_s} \tag{7}$$

where F_{bm} can be expressed in terms of the irradiance F_{tot} perpendicular to the horizontal plane as $F_{\text{bm}} = F_{\text{tot}} f_{\text{bm}}/\cos\theta_s$, 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 (L):

$$\frac{dI}{dL} = -\frac{\Omega(\theta_v)G(\theta_v)I}{\cos\theta_v} + \frac{F_{\text{tot}} f_{\text{bm}} \omega}{4\pi \cos\theta_v \cos\theta_s} \times \Omega(\theta_v)G(\theta_v)P(\theta_s, \phi_s, \theta_v, \phi_v)\, \Omega(\theta_s) e^{-\Omega(\theta_s)G(\theta_s)L/\cos\theta_s}. \tag{8}$$

Here, the first term on the right side is the penetration of beam radiation and the second term is the contribution from scattered radiance. 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_{LD}), leaf diffuse transmittance (T_{LD}), and leaf specular reflectance (R_{LS}). For plant canopy radiative transfer, the scattering transfer function Γ is more commonly used (Ross, 1981; Shultis and Myneni, 1988). There is a relationship between P and Γ (Shultis and Myneni, 1988):

$$\frac{\omega P(\theta_s, \phi_s, \theta_v, \phi_v)}{4\pi} = \frac{\Gamma(\theta_s, \phi_s, \theta_v, \phi_v)}{\pi G(\theta_s)} \tag{9}$$

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

$$dI_{\text{lb}} = \frac{F_{\text{tot}} f_{\text{bm}}}{\cos\theta_s} \times \Omega(\theta_s) e^{-(\Omega(\theta_s)G(\theta_s)/\cos\theta_s)L} \times \frac{\Gamma(\theta_s, \phi_s, \theta_v, \phi_v)}{\pi G(\theta_s)} \times \frac{\Omega(\theta_v)G(\theta_v)}{\cos\theta_v} dL. \tag{10}$$

dI_{lb} attenuates via a plant canopy by $e^{-\Omega(\theta_v)G(\theta_v)(L_c-L)/\cos\theta_v}$, therefore, the observable radiance at the bottom of the canopy is:

$$dI_{\text{lb}} = \frac{F_{\text{tot}} f_{\text{bm}}}{\cos\theta_s} \times \Omega(\theta_s) e^{-(\Omega(\theta_s)G(\theta_s)/\cos\theta_s)L} \times \frac{\Gamma(\theta_s, \phi_s, \theta_v, \phi_v)}{\pi G(\theta_s)} \times \frac{\Omega(\theta_v)G(\theta_v)}{\cos\theta_v} e^{-(\Omega(\theta_v)G(\theta_v)(L_c-L)/\cos\theta_v)} dL. \tag{11}$$

2.1.2. Scattering transfer function with specular reflection

The general form of the scattering transfer function Γ_{bm} has been well investigated (Ross, 1981; Shultis and Myneni, 1988). To

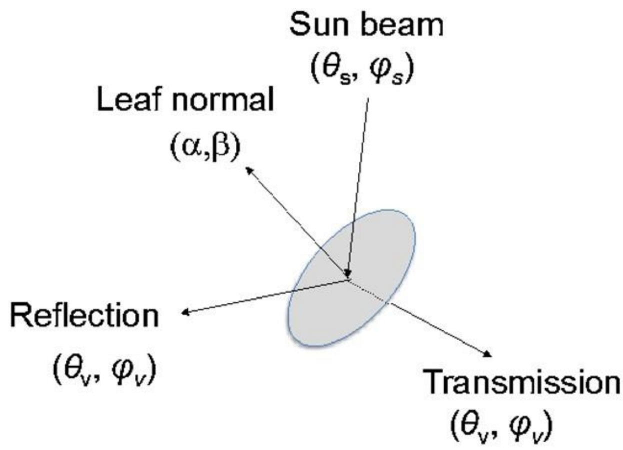

Fig. 1. Schematics of the scattering event on a leaf with a leaf normal (α, β).

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 erectrophile (includes many vertical leaves). Thus, ρ_{bm} is the sum of diffuse ρ_D and specular ρ_{SP} components:

$$\rho_{bm} = \rho_D + \rho_{SP} \tag{12}$$

For ρ_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):

$$\rho_D = \frac{H_T + H_R}{2\pi}, \tag{13}$$

where,

$$H_T = -T_{LD} \int_0^{2\pi} \int_0^{\frac{\pi}{2}} F(\theta_v, \phi_v, \alpha, \beta) F(\theta_s, \phi_s, \alpha, \beta) g(\alpha) d\alpha d\beta$$

and

$$H_R = R_{LD} \int_0^{2\pi} \int_0^{\frac{\pi}{2}} F(\theta_v, \phi_v, \alpha, \beta) F(\theta_s, \phi_s, \alpha, \beta) g(\alpha) d\alpha d\beta.$$

The ratio of projected leaf area to tactual leaf area with the zenith angle of leaf normal (α) and the azimuth angle of leaf normal (β) in the direction of the sun is given by:

$$F(\theta_s, \phi_s, \alpha, \beta) = \cos\theta_s \cos\alpha + \sin\theta_s \sin\alpha \cos(\phi_s - \beta) \tag{14}$$

The ratio of projected leaf area with α and β in the sensor view direction, $F(\theta_v, \phi_v, \alpha, \beta)$, can also be given by the same equation by replacing θ_s, ϕ_s with θ_v, ϕ_v. The product of $F(\theta_v, \phi_v, \alpha, \beta)$ and $F(\theta_s, \phi_s, \alpha, \beta)$ 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 (ρ_{SP}) was computed using the method of Vanderbilt and Grant (1985) and Nilson (1990).

$$\rho_{SP}(\theta_s, \phi_s, \theta_v, \phi_v) = \frac{1}{8} g(\alpha) f(\alpha_0) r_{sp}(\alpha_0), \tag{15}$$

where $\alpha_0 = \cos^{-1}(r_s r_L)$, and f is a correction factor for Fresnel reflectance. Because a leaf surface is not perfectly flat, this factor is needed to reduce the influence of Fresnel reflection (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:

$$f(\alpha_0) = \begin{cases} \cos\theta_v \exp\left(\dfrac{-2k\tan\alpha_0}{\pi}\right), & \text{(abaxial)} \\ f_{ada}\cos\theta_v \exp\left(\dfrac{-2k\tan\alpha_0}{\pi}\right), & \text{(adaxial)} \end{cases}, \tag{16}$$

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_{ada} is an additional correction factor for the adaxial side. When $f_{ada} = 1$, both the abaxial and adaxial sides have the same characteristics. When $f_{ada} < 1$, 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):

$$\alpha = \cos^{-1}\left(\frac{\cos\theta_s + \cos\theta_v}{2\cos\alpha_0}\right) \tag{17a}$$

and

$$\beta = \cos^{-1}\left(\frac{\sin\alpha_0 + \sin\theta_v \cos\phi_v}{2\cos\alpha_0 \sin\alpha}\right). \tag{17b}$$

If $0 < \alpha < \pi/2$, specular reflection occurs on the adaxial (top) side, and if $\pi/2 < \alpha < \pi$, then it occurs on the abaxial (bottom) side. f_{ada} 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 the leaf surfaces. In such cases, $f_{ada} = 1$. In contrast, most tree species show distinct differences in leaf surface flatness ($f_{ada} < 1.0$).

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 (=1 − R_{LD} − R_{LS} − T_{LD}):

$$T_d(L) = \exp(-\sqrt{\ }\,\Omega_{mean} K_{de} L), \tag{18}$$

where Ω_{mean} is the mean clumping index from a viewing zenith angle of 0–90° and is computed by $2\int_0^{\pi/2} \Omega(\theta_s)\cos\theta_s \sin\theta_s d\theta_s$. 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.