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Simple parameterizations of the radiation budget of uniform broadleaved and coniferous canopies

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Abstract

Simulations of the different components of the spectral radiation budget of structurally simple leaf and shoot canopies with varying canopy leaf area index (LAI) were performed. The aims were (1) to test a proposed parameterization of the budget using two spectrally invariant canopy structural parameters (p and p_t) governing canopy absorption and transmittance, respectively, and (2) to incorporate the effect of within-shoot scattering in the parameterization for shoot canopies. Results showed that canopy spectral absorption and scattering were well described by a single parameter, the canopy p value or 'recollision probability', which was closely related to LAI. The relationship between p and LAI was however different in leaf and shoot canopy: e.g., at the same LAI the recollision probability was larger in the shoot canopy. It was shown that the p value of the shoot canopy could be decomposed into the p value of an individual shoot (p_{sh}) and the p value of the leaf canopy with the same effective LAI (LAI$_e$). The canopy p value allows calculation of canopy absorption and scattering at any given wavelength from the leaf (or needle) scattering coefficient at the same wavelength. To calculate canopy reflectance, separation of the downward and upward scattered parts is needed in addition. The proposed parameter p_t worked rather well in the leaf canopy at moderate values of LAI, but not in the coniferous shoot canopy nor at high values of LAI. However, the simulated fraction of upward scattered radiation increased in a straightforward manner with LAI, and was not particularly sensitive to the leaf (or needle) scattering coefficient. Judged by this 'smooth' behavior, the existence of another kind of simple parameterization for this separation remains an interesting possibility.

Keywords: LAI; Vegetation canopy; Parameterization; Spectra; Radiative transfer

1. Introduction

The basic premises for optical remote sensing of vegetation are that the solar radiation received by a remotely located sensor (e.g., on a satellite) upon interaction with the vegetation canopy carries in it the signature of the canopy, and that this spectral signature can be deciphered to obtain the information of interest (Goel, 1988, 1989). Physically based methods for the assessment or monitoring of vegetation parameters (e.g., structural and biophysical characteristics) have progressively become more and more attractive since they are better suited for many current large-scale applications than the traditionally used statistical (empirical) techniques (Knyazikhin et al., 1998b). The parameters of interest vary with the area of application (production ecology, global change monitoring, climate models, etc.); however, for all applications good models of the shortwave radiation budget of vegetation canopies are needed to interpret the remotely sensed signal. The short-wave 'radiation budget' describes how the fractions of radiation absorbed by or scattered out from the canopy to the underlying soil and understorey or back to space (canopy reflectance or albedo) are related to the structural and optical properties of canopy and background.

Given a detailed description of a single canopy, the radiation budget can be calculated using Monte Carlo simulation models (Disney et al., 2000). However, the simulation results are case specific and difficult to generalize

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in lack of knowledge on which of the various canopy characteristics used as input are the most important. To be more generally and operationally applicable, models should build upon a canopy representation with only a small set of basic parameters which govern the radiation budget with sufficient accuracy.

Knyazikhin et al. (1998a,b) analyzed the multiplication factor eigenvalues of the radiative transfer equation for vegetation canopies to find such set of parameters (see Bell & Glasstone, 1970, Section 1.5e). They proposed that, to a good approximation, the amount of radiation absorbed by a canopy should depend only on the wavelength and a canopy structural parameter (p), which is wavelength independent. The parameter p can be interpreted as the probability that a photon scattered from a leaf in the canopy will interact within the canopy again—the "recollision probability". Knowing the p value of a canopy, the scattering coefficient of the canopy at any wavelength can be predicted from the leaf scattering coefficient at the same wavelength. Knyazikhin et al. (1998a,b) also introduced a similar parameter (p_t) relating canopy transmittances at two different wavelengths to the leaf scattering coefficients at these wavelengths. Given the absorption (p value) and transmission (p_t value), total reflectance (the upward scattered part of the incident radiation) is also known (because they all sum up to one). The eigenvalue theory thus states that the radiation budget of a vegetation canopy can be parameterized using only two parameters (p and p_t) which, however, depend on canopy structure in a rather complex manner (Panferov et al., 2001; Shabanov et al., 2003; Wang et al., 2003). Although both parameters are related to the canopy leaf area index (LAI), the relationships between p, p_t and LAI in addition may vary with a set of other parameters, including leaf orientation and spatial distribution, and the degree of grouping of the leaves.

In this paper, we study the behavior of the spectral radiation budget of structurally simple model canopies and demonstrate the effect within-shoot scattering has on the budget. We first estimate the canopy spectral scattering coefficient, defined as the ratio of photons exiting the canopy to those initially hitting leaves or needles in the canopy, for simulated canopies of varying leaf area index (LAI) and composed of randomly distributed single leaves ("leaf canopy") or shoots ("shoot canopy"). This is done by photon tracing (Jensen, 2001), where photons of specified wavelength fired into the canopy are followed until they are absorbed or exit the canopy. The structural parameter (p) is estimated by recording the number of interactions between the photons and the canopy.

The shoot canopy differs from the leaf canopy in that a photon hitting a needle on a shoot may undergo several interactions within the shoot before being absorbed or scattered out from the shoot. In a previous paper (Smolander & Stenberg, 2003), we introduced the recollision probability within a coniferous shoot (p_{sh}) and showed that the shoot scattering coefficient could be predicted from p_{sh} using the same relationship as the one proposed to hold true at the canopy level. The result offers a means to account for the within-shoot scattering in models developed primarily for broadleaved canopies. Here, we show that in the shoot canopy, the canopy level recollision probability can be decomposed into p_{sh} and the p value of a leaf canopy with the same "effective LAI". In two canopies with the same effective LAI, the collided and uncollided part of incoming photons (canopy interceptance and zero order transmittance) are the same for both canopies. We derive the relationship between p and canopy LAI in the two model canopies, allowing the total amount of scattered (or absorbed) radiation to be calculated as a function of LAI. Finally, the proposed p_t-method of separating the scattered radiation into downward and upward scattered (i.e. reflected) parts as well as the two-stream model by Ross (1981) is evaluated using the simulation results.

2. Theoretical background and aim of study

2.1. Canopy absorption and scattering

We use the following terminology to separate the fates of photons arriving in a vegetation canopy, assumed to be bounded underneath by a black surface. The portion of photons which do not interact with leaves at all but are transmitted directly to the ground through gaps in the canopy is called the zero order canopy transmittance (t_0). Canopy interceptance (i_0) correspondingly denotes the portion of incoming photons hitting a leaf, and thus we have $i_0+t_0=1$. Notice that i_0 and t_0 depend on the incoming direction of the photons but do not depend on their wavelength (λ). Part of i_0 will be absorbed by the leaves in the canopy, this wavelength dependent part is the canopy spectral absorption ($a(\lambda)$), while another part ($s(\lambda)$) is scattered out from the canopy ($i_0=a+s$). Note that, at this point, s contains both the upward (to the sky) and downward (to the ground) scattered photons. The canopy radiation budget can now be written as:

$$a(\lambda)+s(\lambda)+t_0=1 \tag{1}$$

Panferov et al. (2001) introduced the canopy structural parameter (p), which can be interpreted as the (mean) probability by which a photon scattered from a leaf in the canopy will interact within the canopy again. We call this the recollision probability. On the assumption that the recollision probability remains constant in successive interactions, canopy absorption (a) and scattering (s), normalized by canopy interceptance (i_0, the part of incoming photons not transmitted directly to the ground), are then obtained as:

$$a(\lambda)/i_0=(1-\omega_L(\lambda))+\omega_L(\lambda)p(1-\omega_L(\lambda))+\omega_L(\lambda)^2p^2(1-\omega_L(\lambda))+\ldots=\frac{1-\omega_L(\lambda)}{1-p\omega_L(\lambda)} \tag{2}$$

and

$$s(\lambda)/i_0 = \frac{\omega_L(\lambda) - p\omega_L(\lambda)}{1 - p\omega_L(\lambda)} \tag{3}$$

where ω_L denotes the leaf scattering coefficient (leaf reflectance plus transmittance). Schematically, the fate of the incoming photons can be thought to follow the four-state Markov chain model presented in Fig. 1.

The ratios $a(\lambda)/i_0$ and $s(\lambda)/i_0$ (Eqs. (2) and (3)) represent the portions of photons absorbed and scattered out from the canopy from those initially hitting the canopy, i.e. they can be interpreted as the absorption and scattering coefficients of the canopy. The average number of interactions (n) between a photon and (leaves in) the canopy, furthermore, is obtained as the ratio of canopy to leaf absorption coefficients, that is:

$$n(\lambda) = \frac{1}{1 - p\omega_L(\lambda)} \tag{4}$$

Eq. (4) describes the simple relationship between the recollision probability (p) and the degree of multiple scattering within the canopy.

In our previous paper, the p value of an individual coniferous shoot (p_{sh}) was introduced and was successfully used to describe the absorption and scattering coefficients of the shoot by means of Eqs. (2) and (3) with p replaced by p_{sh} and with ω_L denoting the needle scattering coefficient (Smolander & Stenberg, 2003, Eqs. (4) and (6), p. 366). The shoot scattering coefficient (ω_{sh}) is smaller than that of its needles (ω_L) (except at completely absorbing or completely scattering wavelengths) but the relationship is nonlinear so that the ratio of ω_{sh} to ω_L increases with ω_L and decreases with increasing p_{sh}. It was shown, also, that close to perfect linear relationship existed between p_{sh} and the spherically averaged ratio of shoot silhouette area to total needle area $\left(\overline{STAR}\right)$, allowing p_{sh} to be calculated as $1 - 4\overline{STAR}$. In this study, we test the relationships (Eqs. (2) and (3)) at the canopy level using simulated model canopies composed of randomly distributed and spherically oriented leaves and shoots, respectively. The canopy p values are denoted p_{LC} (leaf canopy) and p_{CC} (coniferous canopy). Further, we derive the relationship between p and canopy leaf area index (LAI) and test the hypothesis that p_{CC} can be decomposed into p_{sh} and the p_{LC} of a leaf canopy with the same effective leaf area index (LAI_e) as:

$$p_{CC} = p_{sh} + (1 - p_{sh})p_{LC}(LAI_e) \tag{5}$$

In the way presented above (Eqs. (1)–(5)), we can relate the canopy spectral absorption and scattering to a single parameter, the canopy p value, which is a function of LAI.

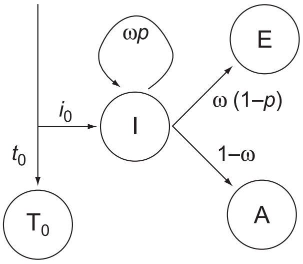

Fig. 1. An illustration of the four-state Markov chain model for canopy absorption and scattering. The photon, coming from the sky, can go through the canopy without interactions with probability t_0, and end up in T_0 (assuming black soil and thus no further scattering). With probability $i_0=1-t_0$ it will interact with the canopy (state I). With probability $1-\omega$ it will be absorbed (state A). With probability ωp it will be scattered by the phytoelement and then hit the canopy again. With probability $\omega(1-p)$ the photon will be scattered by the phytoelement and not hit the canopy again, it will escape (state E).

2.2. Upward and downward scattering

Canopy scattering is divided into upward and downward scattering, of which the former component is of special interest here being the one registered by remote sensing instruments. The upward scattered part of s is called canopy spectral reflectance ($r(\lambda)$). Canopy spectral transmittance ($t(\lambda)$), in turn, is composed of the downward scattered part of s ($t_s(\lambda)$) plus the (wavelength independent) zero order transmittance (t_0). We have then:

$$a(\lambda) + s(\lambda) + t_0 = a(\lambda) + r(\lambda) + t_s(\lambda) + t_0 = 1 \tag{6}$$

When leaves have nonzero absorption, that is $\omega_L<1$, it is easy to decompose the total absorption (a) into first order (a_1) and higher order (a_s) absorption: $a=a_1+a_s$. The photons that are absorbed at the first interaction constitute a_1. The total radiation budget is then:

$$a_1(\lambda) + a_s(\lambda) + r(\lambda) + t_s(\lambda) + t_0 = 1 \tag{7}$$

and, actually, a_1 is easy to calculate: $a_1=(1-t_0)(1-\omega_L(\lambda))$.

Panferov et al. (2001) defined the other structural canopy parameter, p_t, by a simple algebraic combination of leaf and canopy spectral transmittances which, based on both empirical and theoretical analyses, was proposed to eliminate the dependency on wavelength. Using the parameter p_t, canopy transmittance at any given wavelength (λ) is related to that at a reference wavelength (λ_{ref}) by the equation:

$$t(\lambda) = t(\lambda_{ref})\frac{1 - p_t\omega_L(\lambda_{ref})}{1 - p_t\omega_L(\lambda)} \tag{8}$$

Interpretation of the parameter p_t is not as straightforward as that for the parameter p, however, using $\omega_L(\lambda_{ref})=0$, Shabanov et al. (2003, Eq. (3), p. 413) arrived at the relationship:

$$\frac{t(\lambda) - t_0}{t(\lambda)} = \frac{t_s(\lambda)}{t(\lambda)} = p_t\omega_L(\lambda) \tag{9}$$

according to which the product $p_t\omega_L$ is equal to the portion of collided radiation (t_s) from the total canopy transmittance (t).

Using Eqs. (3) and (9), canopy scattering (s) and its division into upward (r) and downward components (t_s) can be solved as a function of the parameters p and p_t:

$$\frac{r(\lambda)}{s(\lambda)} = \frac{s(\lambda)-t_s(\lambda)}{s(\lambda)} = 1 - \frac{t_0 p_t \omega_L(\lambda)(1-p\omega_L(\lambda))}{i_0(\omega_L(\lambda)-p\omega_L(\lambda))(1-p_t\omega_L(\lambda))} \qquad (10)$$

In this paper, the performance of Shabanov's method of separating the total canopy scattering into upward and downward scattered components is tested. We also test the applicability of the model by Ross (1981, Section II.6.4), derived for uniform leaf canopies, on our shoot canopies by incorporating a correction for within-shoot scattering. In the two-component model by Ross, the upward and downward components of radiation inside a canopy are modeled by a pair of differential equations, which in the case of a homogeneous Poisson canopy with spherically oriented Lambertian leaves, yields a good approximate analytical solution.

2.3. Simulation method

Simulations of the different components of the radiation budget (Eq. (7)) were performed for the model canopies with different values of LAI. The aim was to test the proposed parameterization of the radiation budget (Eqs. (1)–(10)), which can be solved knowing the two canopy structural parameters (p and p_t) together with the leaf (needle) scattering coefficient (ω_L) and, in case of the shoot canopy, the parameter p_{sh} related to shoot structure. The canopies were composed of randomly distributed and spherically oriented foliage elements (leaves or shoots), and the underlying soil was assumed black. In the simulations, the incident angle of incoming photons was set to 45°. In addition, the effect of differing incoming angles was studied separately.

The simulation algorithm is as described in Smolander and Stenberg (2003). In short, a number of photons at different wavelengths are fired into the canopy and every photon is followed by photon tracing (a computer graphics method similar to ray tracing, but following a photon in the direction it actually moves; see Jensen, 2001) until it is absorbed by a leaf or a shoot, or exits the canopy. The lengths of the free paths for photons are taken from the exponential distribution, and successive paths are treated independently. (Thus, the model does not include the backscattering hot spot effect.) Zero order canopy transmittance (t_0) and interceptance (i_0) in the model canopies are given by:

$$t_0 = \exp(-GLAI/\cos\theta) \qquad (11a)$$

and

$$i_0 = 1 - \exp(-GLAI/\cos\theta) \qquad (11b)$$

where LAI denotes the leaf area index, θ is the angle of incidence for photons (solar zenith angle), and G is the extinction coefficient, taking the value 0.5 in the leaf canopy. In the shoot canopy, the G value corresponds to $2\overline{STAR}$, where $\overline{STAR}$ is the spherically averaged ratio of shoot silhouette area to total needle area (Oker-Blom & Smolander, 1988). In this study, we used the values $\overline{STAR} = 0.133$ and $p_{sh} = 1 - 4\overline{STAR} = 0.47$ representative of a Scots pine (*Pinus sylvestris* L.) shoot (Smolander & Stenberg, 2003). The value used here for $\overline{STAR}$ implies that the LAI of the shoot canopy must be 88% higher (0.5/0.266=1.88) than the LAI of the leaf canopy to get similar t_0 and i_0 (or that, for similar values of LAI, the effective LAI (LAI$_e$) of the shoot canopy is 47% smaller (0.266/0.5=0.53) than that of the leaf canopy).

3. Results

The basic spectral behavior of the canopy radiation budget is presented in Fig. 2. The most obvious difference between the leaf canopy (Fig. 2A) and the shoot canopy

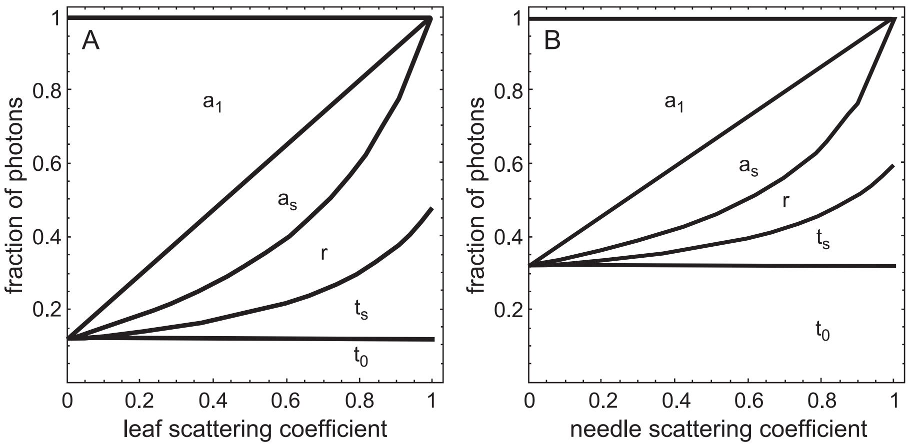

Fig. 2. Schematic presentation of the different components of radiation as a function of the leaf (needle) scattering coefficient for the two model canopies ((A) leaf canopy, (B) shoot canopy) with LAI=3.

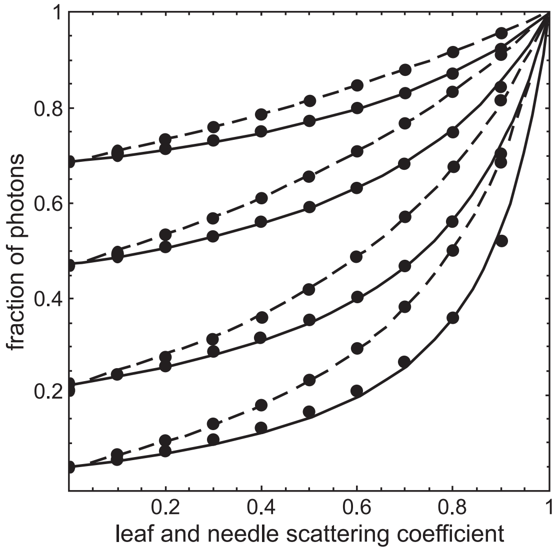

Fig. 3. The non-absorbed component, $1-a=t_0+t_s+r$ (see Fig. 2) of the canopy radiation budget as a function of the leaf (needle) scattering coefficient. The black dots denote values obtained from simulations, and the curves for the shoot canopies (solid lines) and leaf canopies (broken lines) were fitted using Eq. (3). Values of LAI for the shoot canopies were LAI=1 (uppermost curve), 2, 4, and 8 (lowest curve). The leaf canopy LAI values were chosen so, that the effective LAI (LAI_e) was the same for each pair of leaf and shoot canopies.

(Fig. 2B) of the same LAI (here LAI=3) is that because the shoot canopy has a smaller LAI_e, a larger part of the incoming photons goes straight through (larger t_0). This of course causes the other components to be, respectively, smaller for the shoot canopy. Another difference is that, in the leaf canopy, the total absorption ($a=a_1+a_s$) and scattering ($s=r+t_s$) respond more linearly to the element scattering coefficient than in the shoot canopy.

At the same LAI_e, the zero order transmittance (t_0) is equal for the two canopies but the scattered part of i_0 is smaller in the shoot canopy except at completely absorbing or completely scattering wavelengths (Fig. 3). At all other wavelengths the shoot canopy absorbs more than a leaf canopy with the same LAI_e. In both the leaf and the shoot canopy, the fraction of scattered photons as a function of ω_L (plotted in Fig. 3) shows good agreement with Eq. (3), but with different p values.

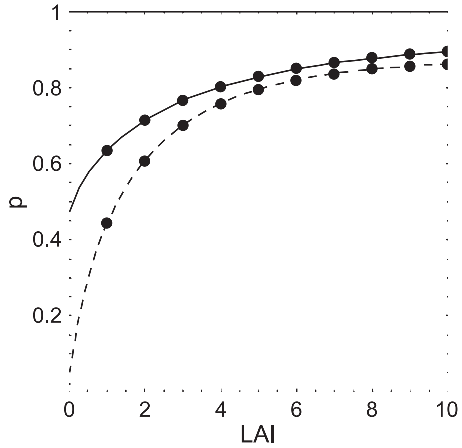

Fig. 5. Parameter p (p_{LC} and p_{CC}) for the leaf and shoot canopy as a function of LAI. Black dots denote the p values solved by Eq. (2) using the simulated absorption data (see Fig. 3). The curve fitted for the leaf canopy (broken curve) is $p_{LC}=p_{LC,max}(1-\exp(-k\text{LAI}^b))$, with $p_{LC,max}=0.88$, $k=0.7$ and $b=0.75$. The curve for the shoot canopy (solid curve) was produced independently using the decomposition formula (Eq. (5)).

Estimated p values of the leaf canopy (p_{LC}) and the shoot canopy (p_{CC}) for different values of LAI are shown in Fig. 4A and B. The parameter p was estimated in two different ways: by fitting Eq. (3) to the simulated canopy and leaf scattering coefficients for different ω_L ("fitted p", shown in Fig. 4), and independently, by calculating the recollision probability by directly counting the interaction events in a single photon tracing simulation with $\omega_L=1$ ("direct p"). As shown in Fig. 4A and B, there is close to perfect agreement (one to one relationship) between the fitted and directly counted values of p. This indicates that to estimate the canopy p value one needs only to perform the photon tracing simulations with one wavelength, instead of performing them for a number of wavelengths and then applying a curve fitting procedure to the data. In Fig. 4C, the value of p_{CC} calculated using the decomposition formula (Eq. (5)) is compared to the fitted p_{CC}, showing good agreement.

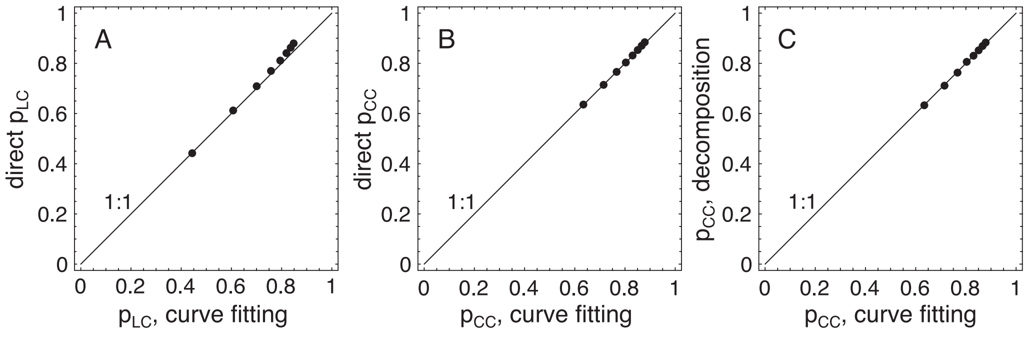

Fig. 4. (A, B) Comparison of p values obtained by fitting Eq. (3) to simulations performed for different ω_L (see Fig. 3), and by direct counting of the photon interaction events for simulations with $\omega_L=1$ ((A) leaf canopy, (B) shoot canopy). (C) Shoot canopy, p_{CC} calculated with the decomposition formula (Eq. (5)) plotted against the fitted values of p_{CC}. The dots represent LAI=1, 2, 3,…, 8.

Fig. 5 presents (i) how the leaf canopy p value (p_{LC}) changes as a function of LAI, and (ii) how the dependence between LAI and the p value of the shoot canopy (p_{CC}) can be predicted from p_{sh} and p_{LC} using the decomposition formula (Eq. (5)). The parameter p_{LC} as a function of LAI was well approximated by the relationship $p_{\mathrm{LC}}=p_{\mathrm{LCmax}}(1-\exp(-k\mathrm{LAI}^{b}))$, with $p_{\mathrm{LCmax}}=0.88$, $k=0.7$ and $b=0.75$. The p value of the shoot canopy (p_{CC}) in turn was very well predicted by the decomposition formula evaluated using p_{LC} of the leaf canopy with similar $\mathrm{LAI}_{\mathrm{e}}$ and $p_{\mathrm{sh}}=0.47$. This confirms our hypothesis that in the shoot canopy the recollision probability can be decomposed into within-shoot and between-shoot recollision probabilities.

Simulations made for different directions (zenith angles) of incoming photons showed that the zenith angle, because it changes the distribution of the points of first interaction within the canopy, has some effect on p_{LC} (Fig. 6). However, for zenith angles less than ca. 50°, the variation in p_{LC} was less than 1.2%. This means that the p value is practically insensitive to the solar zenith angle in the range of solar angles commonly used in satellite remote sensing.

The canopy p value provides the key for calculating canopy absorption and scattering, respectively, but not for separating between the upward (r) and downward (t_{s}) components of the scattered radiation (s). For this purpose, we tested the applicability of the model by Ross (1981) and the parameterization proposed by Shabanov et al. (2003).

In the two-component model by Ross, the upward and downward components of radiation inside a canopy are modeled by a pair of differential equations, shown to give a good approximate analytical solution in the case of a homogeneous Poisson canopy with spherically oriented Lambertian leaves, i.e. corresponding to the leaf canopy in this study. In Fig. 7, simulated values of r and t_{s} in the shoot canopy with LAI=4 are compared to results obtained by the model of Ross (1981). When $\mathrm{LAI}_{\mathrm{e}}$ (=2.13) was used as an input value for the model (instead of the true LAI), the simple components, zero-order transmittance (t_0) and interceptance (i_0), were obtained correctly but the canopy scattering and thus its upward and downward components (r and t_{s}) were overestimated by the model (Fig. 7, broken lines). However, when the correction for within-shoot scattering was included in the model by replacing the needle scattering coefficient (transmittance and reflectance) by that of the shoot (see Smolander & Stenberg, 2003), the curves shifted and the model agreed well with the simulations (Fig. 7, solid line).

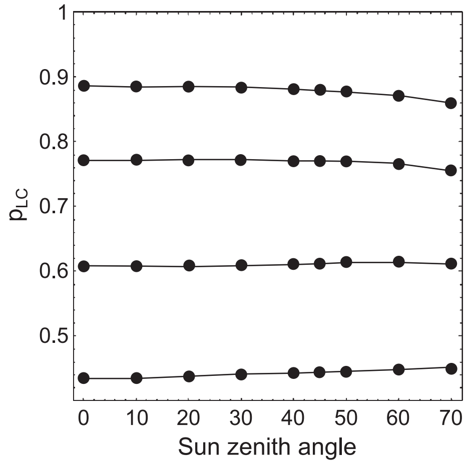

Fig. 6. The effect of solar zenith angle on p_{LC} for LAI=1 (lowest curve), 2, 4, and 8 (highest curve). Black dots denote simulated values.

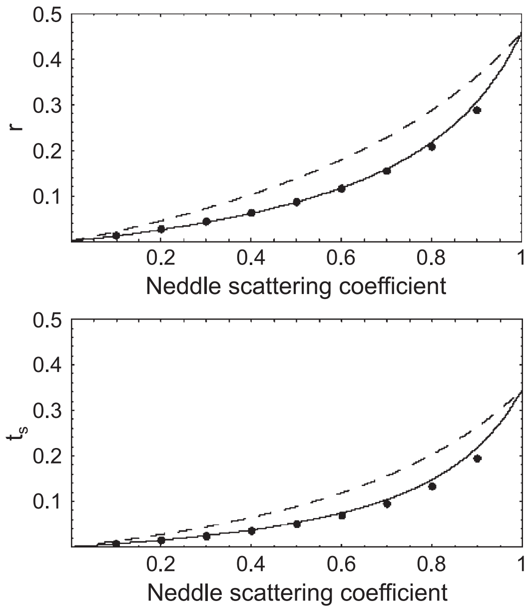

Fig. 7. Demonstration of the effect of including within-shoot scattering in the leaf-based model by Ross (1981). Black dots denote the reflected (r) and transmitted scattered radiation (t_{s}) for the shoot canopy with LAI=4. When the model was used with the effective LAI ($\mathrm{LAI}_{\mathrm{e}}$=2.13) as input, zero order transmittance (t_0) was obtained correctly (not shown here) but components r and t_{s} were overestimated (broken curves). When, additionally, the element scattering coefficient was corrected for by including within-shoot scattering, as suggested by Smolander and Stenberg (2003), the curves shifted and the model fitted well to the simulation data (solid curves).

Simulated values of the ratio of upward to total scattering, $r/(r+t_{\mathrm{s}})$ for the leaf and shoot canopy, as a function of the leaf (needle) scattering coefficient (ω_{L}), are presented in Fig. 8, and compared to results obtained by the models of Ross (1981) and Shabanov et al. (2003). The fraction of upward scattered radiation increased with LAI: for LAI=2 (the lowest curve), approximately 60% of the scattered photons escaped upwards in both the shoot and the leaf canopy, and for LAI=8, the upwards escaping fraction was more than 90% in the leaf canopy (Fig. 8A) and about 80% in the shoot canopy (Fig. 8C). (Notice that values of the effective LAI are smaller in the shoot canopy.) A slight decrease in $r/(r+t_{\mathrm{s}})$ with increasing ω_{L} can be observed. This pattern was correctly mimicked by Ross' model, which generally showed good agreement with the simulations both in the leaf canopy and the shoot canopy (when the shoot level correction was applied). Shabanov's parameterization worked rather well for the leaf canopy at moderate values of

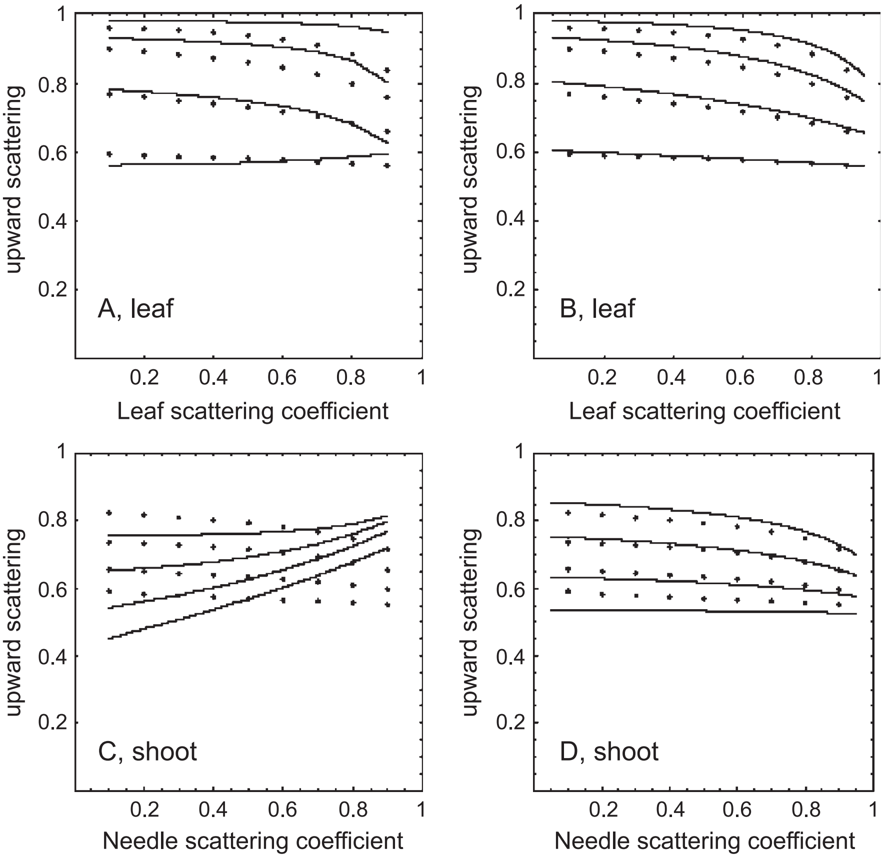

Fig. 8. Simulated values (black dots) of the upward fraction of the total scattered radiation $r/(r+t_s)$ for the leaf and shoot canopies with LAI=2 (lowest dot-line), 4, 6, and 8 (highest dot-line). (A, B) Leaf canopy. (C, D) Shoot canopy. The curves present the results obtained by the p_t-method described by Shabanov et al. (2003) (A and C) and the two-stream model by Ross (1981) (B and D).

LAI (LAI=2 and 4) but not so well for the shoot canopy or for high values of LAI. The curves were produced by Eq. (10), using fixed (i.e. the simulated) values of s and t_0 and the value for p_t giving the best fit to the simulations. Despite this fitting procedure, poor results for the shoot canopy were obtained due to the different shapes of the simulated and calculated curves. The shape of the curve described by Eq. (10) depends in a complex manner on the relation between p and p_t, which explains the different outlook of the curves in Fig. 8A and C. At similar LAI, the shoot canopy has larger p value but smaller p_t value.

To demonstrate the relevance of the shoot-level correction for the interpretation of remote sensing data, we used Ross' (1981) model, with shoot-level correction, to calculate canopy hemispherical reflectance in red and near-infrared (NIR) wavelengths. The leaf (needle) scattering coefficients were set to ω_L=0.1 for red, and ω_L=0.9 for NIR, and the canopies were assumed to be bounded underneath by two different soils with reflectance values of 0.05 and 0.15. Trajectories of leaf and shoot canopy hemispherical reflectance as functions of increasing LAI in the red–NIR plane are presented in Fig. 9. The shoot canopy spectral reflectances change in a different manner and more slowly with increased LAI than those of the leaf canopy, and thus the shoot canopy trajectories occupy a different space in the red–NIR plane than the leaf canopies. Also, an identical signal can result from different canopy and soil combinations. (Note that the hemispherical reflectance values of Fig. 9 are not directly

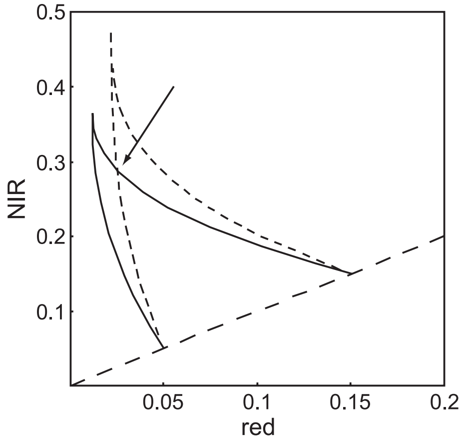

Fig. 9. Trajectories of the hemispherical reflectances of homogeneous leaf canopies (broken curve) and shoot canopies (solid curve) in the red–NIR plane. The trajectories start from the 1:1 soil line at two different soil reflectances: 0.05 and 0.15 (soil reflectance assumed to be the same in red and NIR). A trajectory crossing is indicated by an arrow, where leaf and shoot canopies with different LAI and soil reflectance produce an identical signal in the red–NIR plane: leaf canopy LAI=1.3 and soil reflectance 0.05; shoot canopy LAI=2.7 and soil reflectance 0.15.

comparable to the directional values measured by satellites, but the difference between leaf and shoot canopies should remain approximately the same.)

4. Discussion

The canopy p value holds promising potential to be the single parameter needed to describe the canopy spectral absorption. The results presented here (Figs. 3 and 4) show that the approach works well in the case of simple homogeneous canopies. Based on our previous simulation study (Smolander & Stenberg, 2003), a similar approach works well in describing the spectral absorption of a coniferous shoot. Since also the combination of shoot-level and canopy-level recollision probabilities (Eq. (5), Figs. 4C and 5) worked well, it seems possible that also more complicated canopy structures could be handled in a similar manner. An important part of the usefulness of the p value is its stability under different solar zenith angles (Fig. 6).

The inclusion of the within-shoot scattering, as described by the shoot level p value (p_{sh}), seems to be crucial for realistic modeling of the radiation budget in a coniferous canopy. The effect of the within-shoot scattering is to increase canopy absorption when compared to a broadleaved canopy with the same effective LAI (and thus equal zero order transmittance, t_0). With increased absorption, the scattered components (r and t_{s}) decrease in such a way that in a coniferous canopy they respond more slowly to the increased leaf/needle scattering coefficient than in a broadleaved canopy. Fig. 7 demonstrates this effect: When the model of Ross (1981) was applied to the shoot canopy, parameterized with effective LAI to get the direct component right, the scattered components were too large; but when the element scattering coefficient was corrected using the model by Smolander and Stenberg (2003), the curves "shifted" and matched the simulations well. Application of the model to demonstrate the relevance of the shoot-level correction for the interpretation of remote sensing data (Fig. 9) showed that the inclusion of within-shoot scattering changes the spectral behavior of coniferous forests, as compared to broadleaved forests, in a manner conforming to empirical observations (Tian et al., 2000).

The proposed simple parameterization of the canopy radiation budget included two parameters or "spectral invariants", p and p_{t}. The canopy p value can intuitively be understood to govern canopy absorption through its definition as the "recollision probability", i.e. the probability that a photon scattered from a leaf element will interact in the canopy again. As noted above, the parameter p performed well in estimating the absorption of both homogeneous leaf canopies and homogeneous shoot canopies, and it is reasonable to believe that it should work also in canopies of still more complicated structure.

The other invariant, p_{t}, controls the part of the scattered radiation that exits the canopy downwards. No intuitively simple interpretation such as given for the p value exists, or has yet been found for p_{t}, which can be defined as 'the eigenvalue (normalized by leaf albedo) of the linear operator that assigns downward radiances at the canopy bottom to incoming radiation' (Shabanov et al., 2003). For the simulated leaf canopies, the parameter p_{t} performed relatively well, although the model of Ross (1981) performed slightly better (Fig. 8A and B). The situation was different for shoot canopies, where the p_{t}-based approach predicted that the upwards portion of scattered radiation should increase with increasing needle scattering coefficient, when it was actually decreasing (Fig. 8C). Ross' model, when corrected for effective LAI and for within-shoot scattering, on the other hand performed quite well in explaining the upwards portion of the scattered radiation (Fig. 8D).

It should be noted that Ross' model is formulated only for simple Poisson canopies, and thus is not directly applicable to canopies with nonuniform higher level structure. However, since the shoot-level correction of Smolander and Stenberg (2003) was able to extend the applicability of the model from Poisson leaf-canopies to Poisson shoot-canopies, it seems possible that a similar correction could work also for models with nonuniform higher level structure. The 'smooth' behavior of the simulated fraction of upward scattered radiation with increasing LAI (Fig. 8) moreover suggests that the parameterization approach for this separation remains an interesting possibility.

5. Conclusions

In short, results from this study confirmed that the spectral absorption and scattering of structurally simple uniform canopies can indeed be well described by a single parameter, the canopy p value, which furthermore showed a close relationship with the LAI but insensitivity to the solar zenith angle. Shabanov et al. (2003) have proposed a similar parameter for separating the upward and downward parts of the scattered radiation. Unfortunately, based on the model simulations, this parameter does not seem to work when the shoot-level complexity is added to the canopy structure. The existence of another kind of simple parameterization for this separation however appears as a realistic assumption judged by the straightforward dependence of the ratio of upward to total scattered radiation on LAI, and its insensitivity to the leaf (needle) scattering coefficient. Another matter, not treated in this study, is what controls the directional distribution of the upward scattered (i.e. reflected) radiation. Ultimately, the goal would be a parameterization including tools also for calculating the bidirectional reflectance factor (BRF) of the canopy.

Many satellite instruments measure canopy reflectance from nadir only, and even though there are instruments that produce multidirectional data that can be used to estimate the total upwards component (see Zhang et al., 2002), one would usually like to work with a model that accepts one-directional satellite data as input. Since the directional distribution of reflected radiation is not uniform, the satellite nadir readings do not as such contain enough information to estimate the total upwards scattered portion. Or, the other way around, nondirectional models for canopy radiation budget are not as such sufficient for use in satellite image interpretation. This issue is further complicated by the effect of crown shape on the directional reflectance distribution (Gerard & North, 1997; Rautiainen et al., 2004).

We think that simple parameterizations, when possible, will help to conceptualize and summarize the behavior of more complicated radiation budget models. They may also be useful when one tries to invert the more complicated models for operational satellite image interpretation purposes.

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