Remote Sensing of Environment 137 (2013) 12–16

Contents lists available at SciVerse ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

A new approach for simulating forest albedo based on spectral invariants

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ARTICLE INFO

Article history:
Received 8 February 2013
Received in revised form 9 April 2013
Accepted 22 May 2013
Available online 24 June 2013

Keywords:
Albedo
Absorption
Photon recollision probability
Reflectance model
Boreal forest

ABSTRACT

A simple approach for simulating forest albedo based on the spectral invariants theory was applied to produce the black-sky albedos of 644 boreal forest stands composed of Scots pine, Norway spruce and Silver birch. Results were compared to those simulated using a detailed forest radiative transfer model with input from an extensive forest inventory database. The model based on the spectral invariants produced similar ranges of albedo values for the stands of all species as the detailed model, indicating that despite its simplicity and limited input variables it is flexible enough when predicting the albedo of a forest.

1. Introduction

Physically-based reflectance models quantifying the complex interaction between forest structure and albedo provide a rigorous method for predicting how the currently ongoing changes in forest area and biomass will influence the global albedo. Incorporating the important effect of canopy structure on forest albedo is essential for these models to be realistic, especially in areas where coniferous species are present (Knyazikhin et al., 2012). However, explicit 3D modelling of forest structure is too computer-intensive to be used in operational albedo models, and the detailed input is rarely available.

In this paper, we present a new approach for calculating the shortwave radiation budget of a vegetation canopy. We derive simple formulae for canopy and ground absorptance, and the albedo component is derived as the complement of their sum. The approach is based on the novel spectral invariants theory (the 'p-theory') (for overview, see Knyazikhin et al., 2011), where a single parameter (p) provides the link between the absorption and scattering properties at leaf and canopy levels and quantifies the grouped structure of vegetation. Another spectrally invariant parameter, the asymmetry parameter (q) (Mõttus & Stenberg, 2008), is used to separate the upward (reflectance) and downward (transmittance) scattered fractions. Our research hypothesis is that these spectrally invariant parameters offer an efficient means to couple forest canopy structure and albedo. The hypothesis was tested by simulating and intercomparing the albedos of a large set of forest stands using the new approach and a conventional forest reflectance and transmittance model (FRT, Kuusk & Nilson, 2000) which includes properties of both geometric-optical and radiative transfer equation based models and requires detailed input.

2. Model description

Previously, the p-theory was applied in the forest reflectance model (PARAS) developed by Rautiainen and Stenberg (2005). The model was further extended by Manninen and Stenberg (2009) to include multiple order interactions between canopy and ground (forest floor), and was used for simulating albedo. Here, we present a new member of the PARAS model family which includes calculation of the two other components of the canopy radiation budget: absorption by the canopy and the ground, respectively. The albedo component derived using the new approach agrees with the formula of Manninen and Stenberg (2009) in the case of Lambertian ground reflectance and symmetric upward and downward scattered radiation fractions.

All the PARAS models include only a limited set of parameters and canopy structure is quantified by a single parameter, p—the photon recollision probability (Smolander & Stenberg, 2005). Unlike specialized bidirectional reflectance distribution function (BRDF) models, the PARAS model is better served to simulate the albedo as detailed information on the directional distribution of the scattered radiation is not needed but only the ratio of upward scattered radiation to total canopy scattering.

In the PARAS albedo model, the spectral absorption and scattering coefficients (α_C and ω_C) of the canopy are obtained as simple functions

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http://dx.doi.org/10.1016/j.rse.2013.05.030

of the spectrally invariant parameter (p) and the leaf single scattering albedo (ω_L) at a given wavelength:

$$\alpha_C = \frac{1-\omega_L}{1-p\omega_L} \tag{1}$$

and

$$\omega_C = \frac{\omega_L - p\omega_L}{1-p\omega_L}. \tag{2}$$

The coefficients α_C and ω_C are defined as the fractions of the canopy interceptance (i_0) that are absorbed and scattered from the canopy, respectively (Smolander & Stenberg, 2005). A fraction (Q) of the scattered component ($i_0\omega_C$) is scattered upward and escapes the canopy, and the remaining fraction $(1 - Q)$ is scattered downward. Another part of the incoming photons at any specific wavelength, the zero order transmittance, is transmitted to the ground through gaps in the canopy. The sum of the zero-order transmittance ($t_0 = 1 - i_0$) and the downward scattered part of i_0, $t_{BS} = t_0 + (1 - Q) i_0\omega_C$ equals the total canopy transmittance for the "black soil" (BS) case (Knyazikhin et al., 1998). In the case of non-zero background reflectance, however, part of t_{BS} (re)interacts with the canopy after being reflected from the ground.

We define total canopy spectral absorptance (A_C) as the fraction of the incoming photons at a specific wavelength that eventually is absorbed by the canopy. The total spectral ground absorptance (A_G), correspondingly, is the fraction of the incoming photons absorbed by the ground. The spectral *albedo* (R_C), or the fraction of the incoming photons that escapes the canopy upward, is then obtained as:

$$R_C = 1 - A_C - A_G. \tag{3}$$

In the approach presented here, the albedo is calculated using two additional simplifying assumptions allowing A_C and A_G to be derived with help of geometric series. First, we assume that the fractions of backward scattering (Q) and forward scattering $(1 - Q)$ do not depend on whether the canopy is irradiated from above or below. Secondly, we assume the ground reflectance (ρ_G) to be purely Lambertian. (The first assumption was used also in the simulations by Manninen and Stenberg (2009) but the snow albedo was modelled as combination of completely forward/backward and Lambertian scattering.) The fraction of the isotropic radiation incident from below (i.e. reflected from the ground) which is intercepted by the canopy is called the canopy diffuse interceptance (i_D), and is given by:

$$i_D = \frac{1}{\pi}\int_{2\pi} (1 - t_0(\Omega)) \cos\theta d\Omega. \tag{4}$$

In Eq. (4), $t_0(\Omega)$ denotes the canopy gap fraction in the direction (Ω), θ is the zenith angle of Ω and integration is performed over the solid angle (2π) of the upper hemisphere.

We proceed to derive canopy absorptance (A_C) as the sum of two components: (1) photons incident from the above that get absorbed after one or several interactions within the canopy only (i.e. never reaching the ground), and (2) photons absorbed by the canopy after being reflected from the ground once or several times. The two components, $A_{C,BS}$ and $A_{C,S}$, represent the solutions to the "black soil (BS) problem" and the "soil (S) problem", respectively (Knyazikhin et al., 1998).

The solution to the "BS-problem", $A_{C,BS}$, is simply given by (see Eq. 1):

$$A_{C,BS} = i_0\alpha_C. \tag{5}$$

The solution to the 'S problem', specified by no input energy at the top but Lambertian energy sources at the bottom of the canopy (Ganguly et al., 2008), in turn is obtained as the sum of a geometric series:

$$A_{C,S} = \frac{t_{BS}\rho_G i_D \alpha_C}{1 - Q\omega_C i_D \rho_G} = \frac{[t_0 + i_0(1-Q)\omega_C]\rho_G i_D \alpha_C}{1 - Q\omega_C i_D \rho_G}. \tag{6}$$

The first term of the series (the scale factor), $t_{BS}\rho_G i_D\alpha_C$, corresponds to the fraction of t_{BS} that is reflected from the ground (ρ_G) and then intercepted and absorbed by the canopy ($i_D\alpha_C$) after only one interaction with the ground. The common ratio of the series, $Q\omega_C i_D\rho_G$, in turn describes the event that a photon reflected from the ground is scattered backwards ($Q\omega_C i_D$) and reflected once more from ground (ρ_G).

The sum of $A_{C,BS}$ and $A_{C,S}$ gives total canopy spectral absorptance:

$$A_C = i_0\alpha_C + \frac{[t_0 + i_0(1-Q)\omega_C]\rho_G i_D \alpha_C}{1 - Q\omega_C i_D \rho_G}. \tag{7}$$

We note that Eq. (7) coincides with previously derived expressions for canopy absorptance (e.g. Eq. 6 of Wang et al., 2003), when canopy reflectance and absorptance for the "S-problem" (r_S and a_S) are evaluated as $r_S = Q\omega_C i_D$ and $a_S = i_D\alpha_C$.

The total ground absorptance (A_G) similarly is obtained as the sum of two components: (1) photons incident from above that are transmitted downward through the canopy and are absorbed by the ground at the first interaction ($A_{G,BS} = t_{BS}(1 - \rho_G)$), and (2) photons absorbed by the ground after being reflected from the ground once or several times ($A_{G,S}$).

The solution to the "S-problem", $A_{G,S}$, is obtained as the sum of a geometric series with the same common ratio as for $A_{C,S}$:

$$A_{G,S} = \frac{t_{BS}\rho_G i_D Q\omega_C(1-\rho_G)}{1 - Q\omega_C i_D \rho_G} = \frac{[t_0 + i_0(1-Q)\omega_C]\rho_G i_D Q\omega_C(1-\rho_G)}{1 - Q\omega_C i_D \rho_G} \tag{8}$$

where the scale factor, $t_{BS}\rho_G i_D Q\omega_C(1 - \rho_G)$, corresponds to the fraction of t_{BS} that is reflected once (ρ_G), intercepted and scattered downward ($i_D Q\omega_C$) by the canopy and then absorbed by the ground $(1 - \rho_G)$.

The total ground absorptance is now obtained as:

$$A_G = [t_0 + i_0(1-Q)\omega_C](1-\rho_G) + \frac{[t_0 + i_0(1-Q)\omega_C]\rho_G i_D Q\omega_C(1-\rho_G)}{1 - Q\omega_C i_D \rho_G}. \tag{9}$$

We note that the ground absorptance by Eq. (9) equals canopy transmittance (Eq. 5 of Wang et al., 2003) multiplied by $(1 - \rho_G)$.

The spectral albedo (R_C), finally, is obtained by combining Eqs. (3), (7), and (9).

3. Material and methods

3.1. Forest stands

The material for the albedo simulations comprised 166 Scots pine (*Pinus sylvestris* L.), 87 Norway spruce (*Picea abies* (L.) Karst), 5 birch (*Betula pendula* Roth or *Betula pubescens* Ehrh.) and 386 mixed stands located in three different sites, Puumala, Saarinen and Hyytiälä, in Central and Eastern Finland. The stands represent the typical range in stand structures, development classes and site fertility types of managed boreal forests in Finland. The forest inventory database collected for the sites includes canopy gap fractions and leaf area index ($\mathrm{LAI_{PCA}}$) measured with the LAI-2000 Plant Canopy Analyzer and species-specific values of stand density, diameter at breast height (DBH), tree height, and crown length and radius measured as part of routine stand inventory (Table 1). More details on the measurements are provided by Stenberg et al. (2004), Rautiainen et al. (2009) and Korhonen et al. (2011).