Remote Sensing of Environment 189 (2017) 118–131

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

Radiation budget of vegetation canopies with reflective surface: A generalization using the Markovian approach

J.L. Silván-Cárdenas*, N. Corona-Romero

Centro de Investigación en Geografía y Geomática "Ing. Jorge L. Tamayo", A.C. Contoy 137, Lomas de Padierna, Mex. D.F., CP 14240, Mexico

A R T I C L E I N F O

Article history:
Received 25 April 2016
Received in revised form 14 November 2016
Accepted 21 November 2016
Available online xxxx

Keywords:
Canopy spectral invariants
Photon recollision probability
Interaction coefficient
Canopy interceptance
Canopy radiation budget

A B S T R A C T

Empirical and theoretical evidence has shown that the scattering and absorptance of a homogeneous leaf canopy with black soil can be modeled using simple algebraic combinations of two spectrally invariant parameters (the recollision probability and the canopy interceptance) and one spectrally dependent quantity (the single scattering albedo of an average phytoelement). This study generalizes such results for vegetation canopies composed of one or more types of phytoelements and with a reflective background surface also composed of one or more materials, all of which are treated as endmembers of a nonlinear spectral mixture. The conservative radiation field of a canopy is represented by a finite state Markov chain, such that for a vegetation-surface medium composed of m endmembers, the model is thereby parameterized in terms of an m-length vector of endmember interceptances and an mth-order square matrix containing probabilities of photon recollision amongst the endmembers. Comparisons of some instances of the model with radiative transfer based approximations showed how the latter may overestimate canopy reflectance and transmittance. The two-endmembers model was also compared with Monte Carlo simulations for spherically-oriented leaf canopies with reflective soil. Results indicated that the analytical model accurately describes the radiation field for a wide range of soil reflectance and LAI values. Simulations also showed that while the zenith angle of the illumination source has a small influence on the recollision probabilities, the LAI value mainly determines these through distinct functional relationships. The application of the model to estimate the canopy radiation field of two coniferous species located on the Mexico City Conservation Land is also demonstrated using airborne hyperspectral measurements.

1. Introduction

The ecosystem dynamics and the vegetation canopy play a central role in the energy balance of the earth, and thus, in global climate change and its variability. This occurs through biophysical and biogeochemical processes, one of which is the land surface-atmosphere exchange of CO_2 by means of photosynthesis of vegetation through which plants transform CO_2 and solar radiation into biomass, latent heat and thermal radiation (Arora, 2003; Tian et al., 2003; Brown, 2002). Given that this vegetation-atmospheric interaction is determined by the vegetation structure and the optical properties of surface and vegetation, it is of utmost importance to understand and monitor the variables that determine canopy absorption, transmission and reflection, *i.e.*, the canopy radiation budget (CRB), which requires modeling the shortwave radiation in vegetation canopies (Huang et al., 2007; Panferov et al., 2001).

Several remote sensing approaches have been developed to understand the relationship between forest spectral properties and structure parameters, *e.g.*, the leaf area index (LAI), the fraction of absorbed photosynthetically active radiation (fAPAR) and biomass. The computation of spectral vegetation indices is one of the oldest methods used for this purpose. The most common broadband indices, such as the normalized difference vegetation index (NDVI), have been shown to become saturated at high LAI values and to be significantly sensitive to the understory or tree species composition, the bright soils and shadows (Cabacinha and de Castro, 2009; Eriksson et al., 2006; Jiang et al., 2006; Myneni et al., 1997). This is because the spectral response of forests is the result from photons interacting with the irregular surface of tree crowns and the understory or the ground surface that is exposed through gaps between them, implying variations in radiometric and structural properties at several scales (Schull et al., 2011; Panferov et al., 2001).

In order to improve the estimation of forest structure parameters based on remote sensing data, methods involving three-dimensional radiative transfer (RT) models of a vegetation surface have been developed to obtain the LAI and fAPAR. While the validity of these

* Corresponding author.
E-mail address: jlsilvan@centrogeo.org.mx (N. Corona-Romero).

http://dx.doi.org/10.1016/j.rse.2016.11.019
0034-4257/© 2016 Published by Elsevier Inc.

models has been widely demonstrated, it is also true that they require stratifying the vegetation according to its structure as well as sufficient knowledge about the ground cover (Myneni et al., 1997). Other approaches, such as narrow band vegetation indices, have been applied to explore the capability of imaging spectroscopy to improve the accuracy of satellite-based retrievals of the boreal forest LAI and species composition. And while these have presented strong linear relationships with the effective LAI of boreal forests and are insensitive to the dominant tree species (Heiskanen et al., 2013), the role of the vegetation structure in the radiation budget is not yet well understood. It is therefore important to test physically-based approaches when attempting to interpret and understand hyperspectral signals (Schull et al., 2011).

The spectral invariants (SI) theory provides a research method to study these relationships. According to this theory, it is the canopy structure what determines the interaction probabilities for photons in canopy vegetation rather than the photon frequency or the optical properties of the canopy. Thus, wavelength dependencies are eliminated through simple algebraic combinations between a phytoelement's albedo and the canopy albedo, yielding two spectrally-invariant parameters known as the recollision probability and the escape probability (Knyazikhin et al., 2011; Schull et al., 2011; Huang et al., 2007). These parameters define the probability that a scattered photon by a phytoelement will be intercepted by the canopy again or will escape from the canopy in a given direction (Knyazikhin et al., 2011; Schull et al., 2011), and they have been shown to be related to structural parameters of vegetation such as the canopy structure (Rautiainen et al., 2009; Mõttus and Stenberg, 2008; Mõttus, 2007) or small-scale canopy structure (Smolander and Stenberg, 2003; Lewis and Disney, 2007).

The SI theory makes the assumption of a black-soil in which photons that escape through the bottom of the canopy are absorbed by the soil with a probability of 1. On the other hand, the soil contribution is modeled through a complementary problem in which soil is regarded as an isotropic source that illuminates the canopy from below, such that a situation similar to the black-soil problem applies, and the complete solution is built from these two special cases (Knyazikhin et al., 1998b; Shabanov et al., 2000; Wang et al., 2003; Knyazikhin et al., 2005). While this decoupling of the soil contribution makes the problem mathematically tractable, it also makes it difficult to evaluate the soil-canopy interactions. Consequently, the portion of transmitted photons that are fed back to the canopy cannot be properly evaluated, resulting in the overestimation of canopy transmittance and reflectance, and requiring the energy conservation principle to be expressed in terms of the soil reflectance (Shabanov et al., 2000,2007).

The present study builds upon previous works (Smolander and Stenberg, 2005; Huang et al., 2007; Silván-Cárdenas and Wang, 2010; Silván-Cárdenas and Corona-Romero, 2015) and uses the Markovian approach to express the canopy radiation budget for canopies composed of one or more types of phytoelements and with a background surface also composed of one or more reflective materials, all of which are considered endmembers of the spectral mixtures measured by remote sensing. Specifically, the objectives of this research were to:

1. generalize previously developed models of the CRB (Smolander and Stenberg, 2005; Huang et al., 2007) to handle an arbitrary number of constituent materials for the canopy and the background surface and to allow an explicit representation of the canopy-surface interaction.
2. compare instances of the general model with previously developed models derived from the spectral invariants theory, the radiative transfer theory and Monte Carlo simulations.
3. demonstrate the application of the model to estimate the CRB and to describe the canopy structure based on estimated model parameters.

This article is organized as follows. Section 2 reviews recent developments in the use of the SI theory to model the shortwave radiation budget. Section 3 presents the derivation and analysis of the general model. Section 4 compares instances of the proposed model with previously developed models. Section 5 demonstrates the application of the model to research the coniferous forest in the southern Mexico City. Section 6 presents the key conclusions from this study.

2. Background

The spectral invariance principle is an important concept both theoretically and practically, since knowing the invariants of the canopy and the single scattering albedo of an average phytoelement (ω_l) at any wavelength makes it possible to reconstruct the radiation field of the canopy at any wavelength (Wang et al., 2003; Smolander and Stenberg, 2005; Mõttus and Stenberg, 2008). Smolander and Stenberg (2005) used two spectrally-invariant parameters, namely the recollision probability p and the canopy interceptance i_0, to model the canopy scattering $s(\lambda)$ and absorptance $a(\lambda)$ of a homogenous canopy bounded at the bottom by a black surface, as expressed in Eqs. (1a) and (1b):

$$s(\lambda) = \frac{(1-p)\omega_l(\lambda)}{1-p\omega_l(\lambda)} i_0 \tag{1a}$$

$$a(\lambda) = \frac{1-\omega_l(\lambda)}{1-p\omega_l(\lambda)} i_0 \tag{1b}$$

The model described above was soon found appropriate to represent the light-canopy interaction at several organization levels, where the recollision probability serves as a scaling parameter that accounts for the cumulative effect of several organization levels (Lewis and Disney, 2007; Knyazikhin et al., 2011). For instance, consider a shoot canopy with a recollision probability p_c, where shoots are themselves needle canopies with recollision probability p_{sh}. The nesting of the two models also takes the form of Eqs. (1a) and (1b) but with the composite recollision probability $p = p_{sh} + p_c(1 - p_{sh})$. This property has been used to explain why coniferous and broadleaf canopies with the same effective LAI exhibit a distinct radiation budget (Smolander and Stenberg, 2003).

Since the recollision probability is a key structural parameter for representing the CRB, several studies have dealt with its estimation. Smolander and Stenberg (2003) estimated the recollision probability of Scots pine using Monte Carlo simulations. For each interaction order, they computed the ratios between the number of intercepted photons and the number of scattered photons from previous interaction, so that the effective value of the recollision probability is a weighted average of such ratios. Smolander and Stenberg (2005) estimated the recollision probability for a canopy of spherically-oriented foliage elements in two ways: first, by fitting the canopy scattering model to simulated scattering with photon tracing, and second by directly counting the interaction events in a single photon tracing simulation, with $\omega_l(\lambda) = 1$. Since both estimations were very similar, they concluded that there is no need to simulate photons of every wavelength. Mõttus (2007) provided several analytical and empirical methods to estimate the recollision probability for leaf canopies with black soil. These were based on exact and approximation formulas from a two-stream solution of the radiative transfer equation for a canopy with horizontal leaves, and from Monte Carlo simulations of canopies with spherically-oriented leaves.