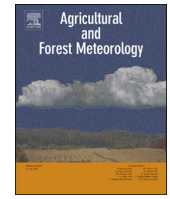
Agricultural and Forest Meteorology 260–261 (2018) 95–108

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

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



Improved kernel-driven semi-empirical bidirectional reflectance factor models for characterizing the reflection of vegetation covers: Considering a specular kernel

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ARTICLE INFO

Keywords:
Bidirectional reflectance factor model
Anisotropy
Vegetation cover
Specular kernel
Multi-angle

ABSTRACT

The kernel-driven semi-empirical BRF (bidirectional reflectance factor) model has been one of the most effective methods for characterizing the distribution of reflection from vegetation covers and it has been used in applications at the regional and global scale. However, our measured BRFs of vegetation cover exhibit a strong forward scattering peak in visible wavelengths and cannot match the model results well. Subsequently, a specular kernel is proposed for inclusion in current BRF models. The advantage of BRF models with a specular kernel is that they can model the reflection peak in the forward scattering, which leads to a notably increased match between modeled BRFs and measured BRFs of vegetation covers at visible wavelengths, and it does not influence the hot spot results of vegetation covers in the backward scattering direction. Moreover, its disadvantage is that the improved BRF models become non-linear models and have two additional free parameters. This relatively simple improvement for BRF models presented here may provide a useful method for describing the reflection of vegetation covers dominated by specular reflection and for characterizing the reflection of vegetation covers with a backward scattering feature.

1. Introduction

Vegetation is an important indicator of several ecosystem properties that influence regional energy balance and global climate (Huete et al., 1994). In the study of ecology on earth, the leaf-, plant- and stand-level measurements have been used to link to land-scapes, regions and continents (Ollinger, 2011). Although many approaches have been suggested by researchers, the unique and central role of remote sensing in investigating vegetated surfaces is universally agreed upon (Asner, 1998; Huete et al., 2002) because of the relationship between the physical properties of vegetation samples and spectral reflectance signals, which has been observed in laboratories, field measurements and then used by remote sensing platforms (Sellers, 1985; Tucker, 1979; Tucker and Sellers, 1986). With the increasing use of off-nadir viewing sensors (Cairns et al., 1999; Deschamps et al., 1994; Diner et al., 1999, 1998), the analysis of the bidirectional reflectance distribution function (BRDF) of vegetation covers using models are increasingly significant for remote sensing community. These valuable investigations offer an opportunity for large-scale studies regarding the response of vegetation to climate change.

Kernel-driven models are one powerful type of BRDF model used to describe the reflection of vegetated land surfaces (Hu et al., 1997; Wanner et al., 1995), and they have been used to study the earth-atmosphere system (Chopping et al., 2008; Lucht et al., 2000; Strugnell and Lucht, 2001; Vermote et al., 1997). Several studies showed that the information regarding the structural and biophysical properties of vegetated land surface may be exploited by directional reflection signals obtained in the field and in the laboratory measurements (Goel, 1988; Kimes, 1983; Kimes et al., 1987, 1986). Moreover, ground-based measurements can also be utilized to examine BRDF models (Roujean et al., 1992; Walthall et al., 1985), to investigate the physical mechanisms of BRDF effects (Sandmeier et al., 1998a, b) as well as the relationships between physical parameters of vegetation samples and BRDF responses (Goel, 1988). However, the results of a number of current bidirectional reflectance factor (BRF) models are not consistent with the measurements of vegetation cover (i.e., planophile type) that presents smooth leaves, which generates specular reflection in the forward-scattering directions in the visible wavelength range (Sandmeier et al., 1998a; Sun et al., 2017b). Such as, the difference between modeled and measured reflection values was approximately 30% over the hemispherical directions (Sun et al., 2017b). We concluded that these BRF models do not consider the specular portion of

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https://doi.org/10.1016/j.agrformet.2018.06.005
Received 14 September 2017; Received in revised form 4 June 2018; Accepted 6 June 2018
0168-1923/

the total reflection measured in the forward scattering direction.

In this paper, we investigated the reflection of vegetation covers dominated by specular reflection and examined the ability of current BRF models to simulate the angular reflection of our vegetation samples. Subsequently, a specular kernel was proposed for current BRF models to counter the high reflection measured in the forward scattering directions and improve their capability of simulating BRF measurements from vegetation covers. With a combination of current BRF models, the specular kernel may be used as an effective tool to study the multi-angular reflection of vegetation.

2. Description of BRF models

In this paper, three linear BRF models and a non-linear model are used to calculate the reflection of our samples, whereas the non-linear model is used to further demonstrate whether our proposal is effective in simulating the BRFs of vegetation cover. The general description of the linear models is as follows:

$$R(\theta_s, \theta_v, \phi) = k_0 + k_1 F_1(\theta_s, \theta_v, \phi) + k_2 F_2(\theta_s, \theta_v, \phi) + \ldots + k_n F_n(\theta_s, \theta_v, \phi) \tag{1}$$

where θ_s represents the illumination zenith angle, θ_v represents the observing zenith angle, φ_s represents the illumination azimuth angle, φ_v represents the observing azimuth angle, and φ represents the relative azimuth angle ($\varphi = \varphi_s - \varphi_v$), k_n represents the parameters that need to be inverted by measurements and F_n represents the kernels derived from either physical or empirical considerations.

2.1. Modified walthall model

This BRF model appropriately expresses the dependence of the reflected signals of vegetation on the primary structure and optical properties of the vegetated surfaces and the measurement geometry, including the incident angle, the observing angle and relative azimuth angle. The linear model is driven by four empirical parameters as follows (Walthall et al., 1985):

$$F_1 = \theta_s^2 + \theta_v^2 \; F_2 = \theta_s^2 \theta_v^2 \; F_3 = \theta_s \theta_v \cos\varphi \tag{2}$$

2.2. Ross-Roujean model

This linear model (Roujean et al., 1992) contains three parameters as follows:

$$F_1 = \frac{1}{2\pi}[(\pi - \phi)\cos\phi + \sin\phi]\tan\theta_s \tan\theta_v - \frac{1}{\pi}[\tan\theta_s + \tan\theta_v + \Delta(\theta_s, \theta_v, \phi)] \tag{3}$$

where Δ describes the horizontal length between illumination and viewing direction as follows (Maignan et al., 2004):

$$\Delta(\theta_s, \theta_v, \phi) = \sqrt{\tan^2\theta_s + \tan^2\theta_v - 2\tan\theta_s \tan\theta_v \cos\phi} \tag{4}$$

and F_2 is obtained by an approximation in which the single scattering is derived from radiative transfer theory for a layer of chaotically oriented and randomly positioned facets with same reflectance and transmittance (Roujean et al., 1992). Multiple scattering between these facets is usually not modeled explicitly and is given by (Litvinov et al., 2011):

$$F_2 = \frac{(0.5\pi - \xi)\cos\xi + \sin\xi}{\cos\theta_s + \cos\theta_v} - \frac{\pi}{4} \tag{5}$$

where ξ represents the phase angle, and its definition is as follows:

$$\cos\xi = \cos 2\alpha = \cos\theta_s \cos\theta_v + \sin\theta_s \sin\theta_v \cos\phi \tag{6}$$

where α (incidence angle) represents half the phase angle.

2.3. Ross-Li model

The difference between the Ross-Li model and the Ross-Roujean model follows the description of F_1 kernel. Because of our dense vegetation cover samples, the Li dense kernel (Li and Strahler, 1992) was selected in this study:

$$F_1 = \frac{(1 + \cos\theta')\sec\theta_s' \sec\theta_v'}{\sec\theta_s' + \sec\theta_v' - O(\theta_s, \theta_v, \phi)} \tag{7}$$

$$O(\theta_s, \theta_v, \phi) = \frac{1}{\pi}(t - \sin t \cos t)(\sec\theta_s' + \sec\theta_v') \tag{8}$$

$$\cos t = \frac{h}{b}\frac{\sqrt{D^2 + (\tan\theta_s' \tan\theta_v' \sin\phi)^2}}{\sec\theta_s' + \sec\theta_v'} \tag{9}$$

$$D = \sqrt{\tan^2\theta_s' + \tan^2\theta_v' - 2\tan\theta_s' \tan\theta_v' \cos\phi} \tag{10}$$

$$\cos\theta' = \cos\theta_s' \cos\theta_v' + \sin\theta_s' \sin\theta_v' \cos\phi \tag{11}$$

$$\theta_s' = \tan^{-1}\left(\frac{b}{r}\tan\theta_s\right), \; \theta_v' = \tan^{-1}\left(\frac{b}{r}\tan\theta_v\right) \tag{12}$$

The two parameters h/b and b/r need to be fixed in the dense kernel, and their values are chosen as $h/b = 2$ and $b/r = 1$.

2.4. Rahman-Pinty-Verstraete model

This model is non-linear and is given in the following form (Rahman et al., 1993):

$$R(\theta_s, \theta_v, \phi) = \frac{(\cos\theta_s \cos\theta_v)^{k-1}}{(\cos\theta_s + \cos\theta_v)^{1-k}}\rho_0 F(\xi)(1 + R(G)) \tag{13}$$

$$F(\xi) = \frac{1 - g^2}{(1 + g^2 - 2g\cos\xi)^{1.5}} \tag{14}$$

$$1 + R(G) = 1 + \frac{1 - \rho_0}{1 + G} \tag{15}$$

$$G = \sqrt{\tan^2\theta_s + \tan^2\theta_v - 2\tan\theta_s \tan\theta_v \cos\phi} \tag{16}$$

where ρ_0, g and k are the inverted parameters, $F(\xi)$ is the Henyey-Greenstein phase function, and $1 + R(G)$ is used to approximate the shadowing hot spot effect (Rahman et al., 1993). These BRF models have been used to model the BRF of natural surfaces by the reflection information from MODerate Resolution Imaging Spectroadiometer (MODIS), Research Scanning Polarimeter (RSP) and Polarization and Directionality of Earth Reflectances (POLDER) (Cairns et al., 1999; Deschamps et al., 1994; Hu et al., 1997; Litvinov et al., 2011). In this study, we do not assess the theory of these BRF models; rather, we focus on the ability of them on modeling the measured BRFs of our vegetation covers.

2.5. Specular kernel in the modified models

A single leaf has a reflection peak in the forward scattering direction (Bousquet et al., 2005), while the randomly oriented leaves reduce this reflection peak (Sandmeier et al., 1998a) because the angular spread of specular reflection can be described by assuming the surface consists of micro-facets (leaves for vegetation cover) that each reflect specularly. The facets, whose normal is same to the nadir direction, contribute to the specular reflection. Thus, the specular reflection can be observed in the forward scattering directions in the multi-angular reflection measurements of vegetation covers (Sandmeier et al., 1998a; Sun et al. 2017a,b,c). The specular portion is simulated by the micro-facet specular model (Cook and Torrance, 1981):

$$F_{spec} = \frac{1}{4\cos\theta_s \cos\theta_v} F(\alpha, n) G(\theta_s, \theta_v, \phi) \frac{P(\beta, \delta)}{P_n} \tag{17}$$