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Research Paper

Modelling of fraction of absorbed photosynthetically active radiation in vegetation canopy and its validation

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The Fraction of Absorbed Photosynthetically Active Radiation (FPAR) has been identified as one of the key parameters in calculating ecosystem productivity. The objective of this paper is to model the vertical profile of FPAR in the canopy using a radiative transfer model, the Modified Simultaneous Heat and Water (MSHAW) radiation model. Model analysis indicated that the vertical distribution of the canopy FPAR was dependent on the leaf area index (LAI), average leaf orientation angle (ALA), solar position, and sky conditions. In the validation of the MSHAW model with three varieties of wheat leaf profile at different growth stages, two parabolic functions were developed to approximately reconstruct the shape of the wheat leaf for the first time and, consequently, the vertical profiles of LAI and ALA used to drive the MSHAW model were estimated. The validation results indicated that the estimated FPAR was close to the measurements made with the SunScan canopy analysis system with an RMSE of approximately 0.15 for the continuous canopy. Finally, this paper also discusses a promising method to perform time normalisation on canopy FPAR data using multiple temporal remotely sensed data observations and to retrieve FPAR from remotely sensed data based on the analysis of the MSHAW model.

1. Introduction

The Fraction of Absorbed Photosynthetically Active Radiation (FPAR) is generally defined as the fraction of the photosynthetically active radiation (PAR) absorbed by the vegetative components in the solar illumination spectra from 400 nm to 700 nm. FPAR is one of the key parameters in the studies of the surface energy flux estimate, climate change, hydrology process, and biomass productivity (Fang & Liang,

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2006; Sellers et al., 1994). Several algorithms have been proposed to generate FPAR from the Advanced Very High Resolution Radiometer (AVHRR) (Sellers et al., 1994), the Moderate Resolution Imaging Spectroradiometer (MODIS) (Myneni, Nemani, & Running, 1997), the Multi-Angle Imaging SpectroRadiometer (MISR) (Knyazikhin, Martonchik, Diner, et al., 1998; Knyazikhin, Martonchik, Myneni, et al., 1998; Zhang et al., 2000), the Carbon Cycle and Change in Land Observational Products from an Ensemble of Satellite CYCLOPES (Baret et al., 2007; Weiss, Baret, Garrigues, & Lacaze, 2007) etc. These methods can be generally classified into two groups: physical methods or look-up table methods from the radiative transfer models, and linear or non-linear methods related to the vegetation index (Gobron, Pinty, Verstraete, & Govaerts, 1999; Goward & Huemmrich, 1992; Johnson & Scholasch, 2005; Roujean & Breon, 1995).

Ground validation to evaluate the accuracy of the FPAR estimates has attracted much attention from the remote sensing community (Claverie et al., 2013; Fang, Wei, & Liang, 2012; Hu et al., 2007; Steinberg, Goetz, & Hyer, 2006; Weiss et al., 2007). The canopy FPAR at ground level is generally determined using instruments such as AccuPAR or SunScan (Liu, Wang, et al., 2011). Because ground-measured FPAR is identified as the true value and is then compared with FPAR retrieved from the remotely sensed data to evaluate the performance of the algorithms, the accuracy of the ground measurement will significantly influence the result of the validation and thus, high accuracy of ground measurement is desired. However, Liu, Wang, et al. (2011) found that the SunScan did not perform as well as expected. After applying an ellipsoidal leaf angle distribution parameter (ELADP) to refine the SunScan calculations, they reduced the error of the instrument itself. To improve the validation results, it is necessary to know exactly how the light interacts with the vegetated elements in the canopy. Many models have been developed for the light distribution and absorption in the canopy, such as the radiative transfer models (e.g., SUIT and SAIL series models (Suits, 1972; Verhoef, 1984)), gap frequency model (Fan, Xu, Liu, Yan, & Cui, 2009; Tao, Fan, Wang, Yan, & Xu, 2009), radiosity-graphics combined model (RGM; Qin & Gerstl, 2000), and Monte Carlo ray-tracing technology (Goel & Thompson, 2000; Govaerts & Verstraete, 1998; Lewis, 1999). However, the current studies using the above models mainly concern the total FPAR of the canopy and lack details about the distribution of the absorbed light in the canopy. As stated in some previous studies (Huang et al., 2011; Wang et al., 2005), the vertical profiles of the vegetation canopy hold much more information to detect the status of the vegetation, and should be paid more attention. From this point of view, the objective of this paper is to model the vertical FPAR profile by using a modified radiative transfer model and perform model analysis and validation on the wheat canopy. As a result, this paper is organised as follows. Section 2 presents the Simultaneous Heat and Water (SHAW) radiative transfer model proposed by Flerchinger and Yu (2007) and an improved version, as well as the simulation of the FPAR. Section 3 analyses the model consistency of some key parameters such as component spectra, canopy leaf area index (LAI), average leaf orientation angle (ALA), solar position and sky diffuse radiance ratio. Section 4 presents the validation of the modified model for wheat canopies at different growth stages. In this section, this paper will also provide a new method to reconstruct the leaf profile shape and calculate the ALA and LAI of the canopy. Section 5 and 6 present the discussions and conclusions, respectively.

2. Methodology

Simulation of the vertical distribution of FPAR in the canopy requires estimation of the flux exchange for each layer within the canopy. After light enters the canopy, it can be reflected, transmitted, scattered and absorbed by plant elements. The process of flux exchange between the canopy layers and soil follows the radiative transfer principle and can be obtained by estimating the downward and upward flux for each layer. As a multi-layer model, the Simultaneous Heat and Water (SHAW) model estimates flux within the canopy layers and bottom layer of soil and/or plant residues using the following equations (Flerchinger & Yu, 2007; Flerchinger, Xiao, Sauer, & Yu, 2009):

$$\begin{aligned} S_{u,i} =& S_{u,i+1}\cdot\tau_{d,i+1} + S_{u,i+1}(1-\tau_{d,i+1})\left(\rho_1 f_{d,\uparrow\uparrow} + \tau_1 f_{d,\downarrow\uparrow}\right) \\ &+ S_{dd,i-1}(1-\tau_{d,i})\left(\rho_1 f_{b,\downarrow\uparrow} + \tau_1 f_{b,\downarrow\downarrow}\right) \\ &+ S_{db,i-1}(1-\tau_{b,i})\left(\rho_1 f_{b,\downarrow\uparrow} + \tau_1 f_{b,\downarrow\downarrow}\right), \end{aligned} \tag{1}$$

where $S_{u,i}$ is the upward radiation of the ith layer, from the top of the canopy to the bottom, $\tau_{b,i}$ and $\tau_{d,i}$ represent, respectively, the fraction of solar direct beam and sky diffuse radiance passing through the ith layer without being obscured by any canopy component, ρ_1 is the leaf reflectance, and τ_1 is the leaf transmittance, $f_{b,\downarrow\downarrow}$ is the fraction of downward radiation that is transmitted downward, and $f_{d,\downarrow\uparrow}$ is the fraction of downward diffuse radiation that is reflected upward, $S_{db,i}$ is the downward radiation of solar direct flux in the ith layer, and $S_{dd,i}$ is the downward radiation of scattering flux.

Following the theory of the radiative transfer model and the formulation of the upward flux, we have shown the method of calculating downward flux, including two different parts: downward direct flux and downward diffuse flux (Liu, Huang, et al., 2011):

$$S_{db,i} = S_{db,i-1}\tau_{b,i},$$

$$S_{db,0} = I_b,$$

$$\begin{aligned} S_{dd,i} =& S_{dd,i-1}\tau_{d,i} + S_{dd,i-1}(1-\tau_{d,i})\left(\rho_1 f_{d,\downarrow\downarrow} + \tau_1 f_{d,\uparrow\downarrow}\right) \\ &+ S_{db,i-1}(1-\tau_{b,i})\left(\rho_1 f_{b,\downarrow\downarrow} + \tau_1 f_{b,\uparrow\downarrow}\right) \\ &+ S_{u,i}(1-\tau_{d,i})\left(\rho_1 f_{d,\uparrow\downarrow} + \tau_1 f_{d,\uparrow\uparrow}\right), \end{aligned} \tag{2}$$

$$S_{dd,0} = I_d.$$

The direct flux is determined solely by the radiation transferred through the gaps, and the downward diffuse radiation contains four parts: i) the diffuse radiation passing through the gap; ii) the downward diffuse radiation reflected and transmitted from the scattering downward radiation of the upper layers; iii) the transmitted and reflected downward direct radiation; and iv) the downward diffuse radiation reflected and transmitted from the scattering upward radiation.