A MODEL FOR INSTANTANEOUS FAPAR RETRIEVAL: THEORY AND VALIDATION

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ABSTRACT

The Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) is a critical input parameter to many climate and ecological models. Its calculation accuracy from remote sensing images directly influences the estimation of net primary productivity (NPP) and carbon cycle. This paper presents a hybrid model combining the characteristics of geometric optic model and radiation transfer model. It considers the illuminated and shadow area of the canopy and soil, as well as the multiple scattering between the canopy and soil. The Monte Carlo simulations of canopy FAPAR are also conducted and the results are compared with model results. In addition, we did the simulation of FAPAR daily change by the model and MC method, and compare the results with field measured daily data of FAPAR. All the results prove the model effective.

***Index Terms*—**Fraction of Absorbed Photosynthetically Active Radiation (FAPAR), Monte Carlo simulation, hybrid model, instantaneous FAPAR, remote sensing retrieval

1. INTRODUCTION

The Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) is the fraction of incoming solar radiation in the spectral range from 400 nm to 700 nm that is absorbed by plants. FAPAR can be derived from remote sensing measurements and a number of algorithms have been proposed to estimate this important environmental variable [1-5]. However, most of the algorithms only consider parameters like normalized differential vegetation index (NDVI), leaf area index (LAI), leaf chlorophyll, and construct the empirical relationships between FAPAR and these parameters [1-3]. It is known that the solar zenith angle also affects the FAPAR, and thus a disadvantage for empirical method is that the relationship varies with the time of a day. To overcome this disadvantage, we present a model for FAPAR retrieval considering the solar zenith angle change besides some known parameters.

2. MODEL FOR FAPAR RETREIVAL

Suppose the sun illuminates the canopy from the zenith angle of θ_s, while the sensor observes from θ_v, the soil background reflectance is ρ_g . Along the light incoming path, the photons could either directly penetrate the canopy and reach the soil (canopy transmittance, denoted by T_0), or interact with leaves, being reflected (canopy directional reflectance, denoted by $\rho_{\theta v,\lambda}$), transmitted or absorbed. The interaction process is shown in figure 1.

The probability of photons directly reaching the soil represents the canopy transmittance:

$$T_0 = e^{-\lambda_0 \cdot \frac{G_s}{\mu_s} \cdot LAI} \tag{1}$$

where λ_0 is the Nilson parameter considering vegetation clumping effect, G_s is the mean projection of a unit foliage area into the plane perpendicular to the solar incidence direction, μ_s is the cosine of solar zenith angle, LAI is the vegetation leaf area index. Canopy directional reflectance $\rho_{\theta v,\lambda}$ along the incoming path is expressed as:

$$\rho_{\theta v,\lambda} = \rho_{c,\lambda}\left(1 - e^{-\lambda_0 \frac{G_v}{\mu_v} \cdot \Gamma(\phi) \cdot LAI}\right) + \beta \cdot \rho_{c,\lambda}\left[e^{-\lambda_0 \frac{G_v}{\mu_v} \cdot \Gamma(\phi) \cdot LAI} - e^{-\lambda_0 \frac{G_v}{\mu_v} \cdot LAI}\right] \tag{2}$$

where $\rho_{c,\lambda}$ is pure vegetation reflectance at wavelength λ, $\Gamma(\phi) = \exp\left(-\frac{\phi}{\pi - \phi}\right)$, ϕ accounts for the sun-target-sensor position and depends on the angle between the solar and viewing direction and the leaf angle distribution (LAD) of canopy, and β is the ratio of scattering light. If we integrate (2) in the 2π space, it represents the single scattering along the incoming path.

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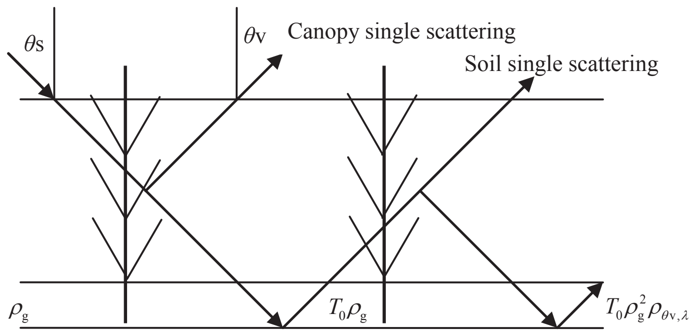

Fig. 1. Interactions of photons with canopy and soil background

Consider that canopy reflectance approximates transmittance, the canopy absorption along the incoming path is:

$$FAPAR_{\theta v,\lambda,0}=1-T_0-2\rho_{\theta v,\lambda}$$

The canopy absorption along the outgoing path of photons reflected from the background is:

$$FAPAR_{\theta v,\lambda,1}=T_0\rho_g-T_0\rho_g T_{\theta v}-2T_0\rho_g\rho_{\theta v,\lambda}=T_0\rho_g\left(1-T_{\theta v}-2\rho_{\theta v,\lambda}\right)$$

Similarly, the canopy absorption along the outgoing path of photons reflected twice from the background is:

$$FAPAR_{\theta v,\lambda,2}=T_0\rho_g^2\rho_{\theta v,\lambda}\left(1-T_{\theta v}-2\rho_{\theta v,\lambda}\right)$$

Thus, canopy directional absorption at wavelength λ is:

$$FAPAR^t_{\theta v,\lambda}=\left(1-T_0-2\rho_{\theta v,\lambda}\right)+\left(1-T_{\theta v}-2\rho_{\theta v,\lambda}\right)\frac{T_0\rho_g}{1-\rho_g\rho_{\theta v,\lambda}}$$

Let $\alpha=\frac{1-T_{\theta v}-2\rho_{\theta v,\lambda}}{1-T_0-2\rho_{\theta v,\lambda}}$, it is simplified:

$$FAPAR^t_{\theta v,\lambda}=FAPAR_{\theta v,\lambda,0}\left(1+\alpha\cdot\frac{T_0\rho_g}{1-\rho_g\rho_{\theta v,\lambda}}\right)\qquad(3)$$

The instantaneous FAPAR is the integral of (3) in the 2π space from 400 to 700 nm:

$$FAPAR^t=\int_{0.4-0.7}d\lambda\int_{2\pi}FAPAR^t_{\theta v,\lambda}d\Omega_v\qquad(4)$$

In the practical calculation, the integral in the 2π space is separated into the double integral of solar zenith angle and azimuth angle. The 2π space FAPAR is written as:

$$\begin{aligned}FAPAR_{2\pi,\lambda}&=\frac{1}{\pi}\int FAPAR_{\theta v,\lambda}\cos\theta d\Omega\\&=\frac{1}{\pi}\int_0^{2\pi}\int_0^{\pi/2}FAPAR_{\theta v,\lambda}\cos\theta\sin\theta d\theta d\varphi\end{aligned}\qquad(5)$$

The integral from 400 to 700 nm can be discretized into:

$$FAPAR^t=\frac{1}{700-400}\left[\begin{aligned}&\sum_{i=1}^{n-1}\frac{FAPAR_{\lambda_{i+1}}+FAPAR_{\lambda_i}}{2}\left(\lambda_{i+1}-\lambda_i\right)\\&+FAPAR_{\lambda_1}\left(\lambda_1-400\right)+FAPAR_{\lambda_n}\left(700-\lambda_n\right)\end{aligned}\right]\qquad(6)$$

where n denotes the band number, $FAPAR_{\lambda_i}$ is the $FAPAR$ value at band i, λ_i (i = 1, 2, …, n-1) is the central wavelength in nanometer of band i. The last two terms in the square brackets are the correction terms when the central wavelength of the start and end band are not exactly equal to 400 nm and 700 nm.

3. COMPARISIONS WITH MONTE CARLO SIMULATIONS

We conducted the Monte Carlo simulations of FAPAR and compared the results with model results [6-8]. The FAPAR for different LAI (figure 2), solar zenith angle (figure 3), soil reflectance (figure 4) and leaf angle distribution (LAD) (table I and II) were calculated by the model and simulated by Monte Carlo method.

The relationships between FAPAR and LAI for MC and model are shown in figure 2. For both MC and model, FAPAR increases with LAI but the rate gradually slows. The value saturates after LAI = 5. The model value is a little lower than MC value, but the difference is limited in a small range, less than 3% when LAI maximizes. The error is caused by the neglect of multiple scattering of photons in the canopy in the model while MC not, and the approximation of canopy reflectance to transmittance. Since multiple scattering increases with LAI, it is understandable that the difference between model and MC results also augments when LAI increase.

Figure 3 shows that FAPAR increases when solar zenith angle becomes larger. The physical reason is the elongation of photon path in the canopy, and hence the higher probability of collision between photons and leaves.

We also analyzed the contribution of background to canopy FAPAR. With the increase of soil reflectance, the canopy absorption along the outgoing path of photons reflected from the background also increases. Thus, the result of a bigger soil reflectance is a higher FAPAR value for vegetation. The model value is a lot lower than MC value when the supposed soil reflectance is higher than 0.6. However, since the real soil reflectance is often less than 0.4 in the PAR region from 400 to 700 nm, the error of the model is actually low. Results imply that canopy absorption along the outgoing path cannot be neglected.

Comparisons of model and MC results for difference LAD are listed in table I when LAI = 3.5 and table II when LAI = 1. Due to the small solar zenith angle (<45°), FAPAR for planophile canopy is largest, spherical is second, and erectophile is smallest. Model value is a little smaller and the error is about 2%, as listed in column 4. The FAPAR value of the model omitting the canopy absorption along the outgoing path are listed in column 3 and corresponding error in the last column. It is easy to see that the average error is larger and exceeds 7% when LAI is low. On the other hand, our presented model considers this contribution and the error is about 2% - 3% compared with Monte Carlo simulation results.

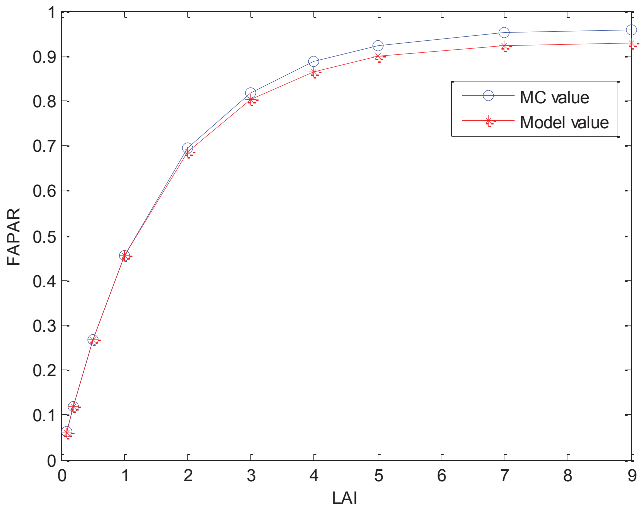

Fig. 2. Relationships between FAPAR and LAI

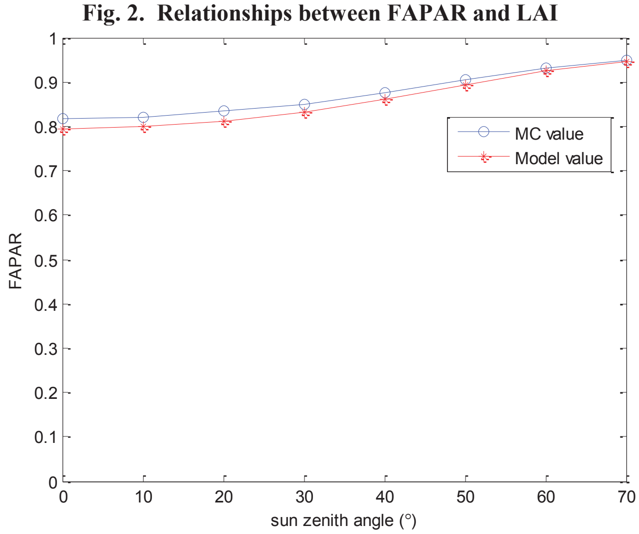

Fig. 3. Relationships between FAPAR and solar zenith angle

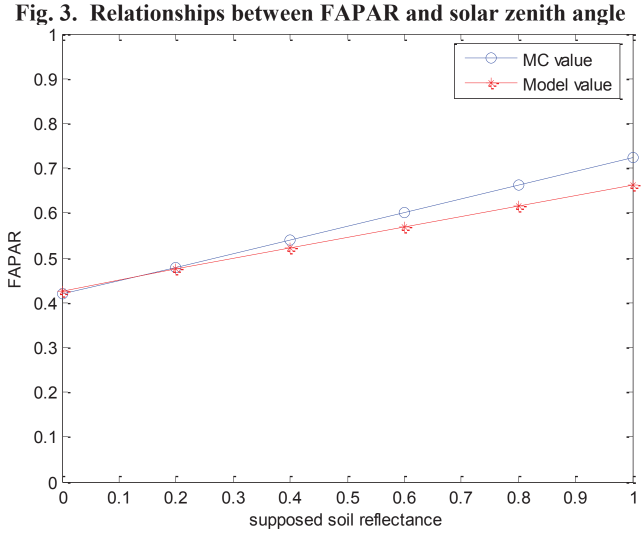

Fig. 4. Relationships between FAPAR and supposed soil reflectance

Table I. Relationship between FAPAR and LAD when LAI value is large

	MC FAPAR	Model FAPAR	Model FAPAR*	Error (%)	Error* (%)
Planophile	0.9080	0.8940	0.8822	1.547	2.837
Spherical	0.8511	0.8321	0.8191	2.239	3.764
Erectophile	0.8297	0.8157	0.8011	1.685	3.445

The results are obtained when LAI = 3.5, $\theta_s = 30°$, $\rho_g = 0.1181$
* represents the case when omitting the canopy absorption along the outgoing path of photons reflected from the background

Table II. Relationship between FAPAR and LAD when LAI value is small

	MC FAPAR	Model FAPAR	Model FAPAR*	Error (%)	Error* (%)
Planophile	0.5517	0.5416	0.5212	1.834	5.526
Spherical	0.4495	0.4458	0.4175	0.819	7.123
Erectophile	0.4440	0.4242	0.3961	4.448	10.780

The results are obtained when LAI = 1, $\theta_s = 30°$, $\rho_g = 0.1181$
* represents the case when omitting the canopy absorption along the outgoing path of photons reflected from the background

4. VALIDATION WITH FIELD DATA

We also further validate the algorithm with field data of daily FAPAR for wheat. The winter field was located at 38° 51’ 26’’ N, 100° 24’ 38’’ E in Zhangye, Gansu Province, China. The PAR data was measured by SunScan probe v1.01 with an interval of half an hour from 8 am. to 8 pm. on Jun 16, 2008. Every time we measured the incoming solar flux $I_{\mathrm{TOC}}^{\downarrow}$, flux to the ground $I_{\mathrm{Ground}}^{\downarrow}$, flux from the ground $I_{\mathrm{Ground}}^{\uparrow}$ and the outgoing solar flux $I_{\mathrm{TOC}}^{\uparrow}$. APAR and FAPAR were calculated with the following two formulas:

$$APAR = I_{\mathrm{TOC}}^{\downarrow} - I_{\mathrm{Ground}}^{\downarrow} + I_{\mathrm{Ground}}^{\uparrow} - I_{\mathrm{TOC}}^{\uparrow}$$

$$FAPAR = APAR / I_{\mathrm{TOC}}^{\downarrow}$$

The daily change of APAR is depicted in figure 5. The curve resembles a sine curve, reaching a peak round 1 pm. at noon. The daily change of FAPAR is shown in figure 6. The curve is similar to a cosine curve, with a trough round 1 pm. Also depicted in figure 6 are the MC and model results. They were simulated or calculated with corresponding leaf reflectance, transmittance and soil reflectance data, LAI, and LAD. Results show that the algorithm, the Monte Carlo method, and the field data share the same daily change trend and similar scale. The error is small and acceptable, proving the feasibility of the proposed model.

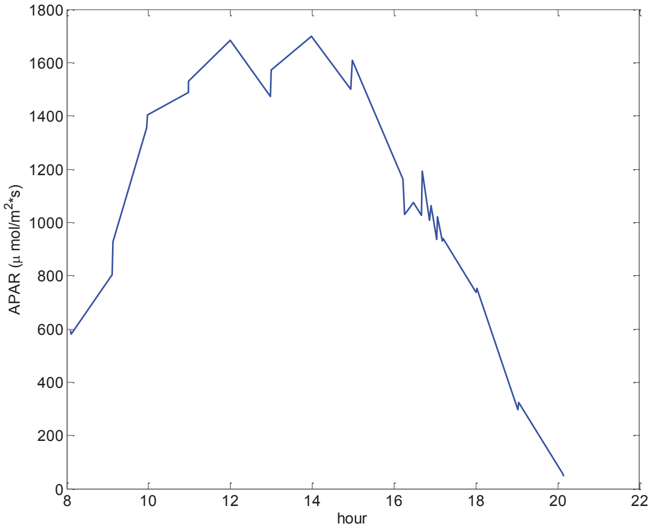

Fig. 5. Daily change of APAR from field measurement

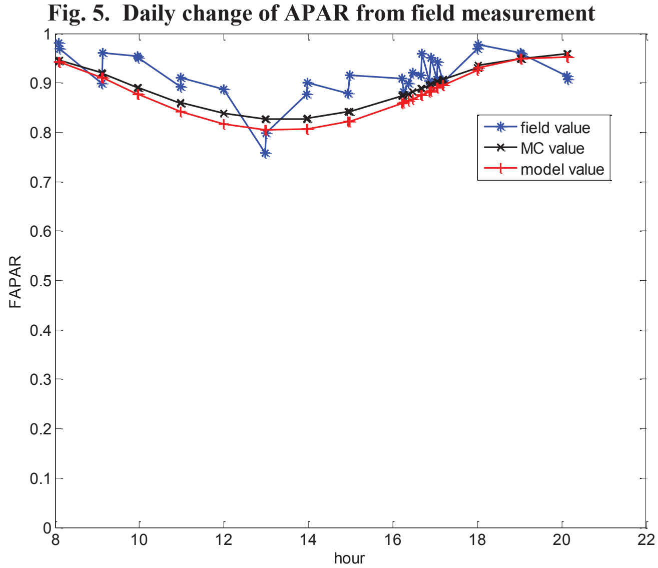

Fig. 6. Daily change of FAPAR from field measurement, MC simulation and model calculation

5. CONCLUSION

A model for instantaneous FAPAR retrieval is proposed in this paper. It is derived by analyzing the interaction processes of photons and canopy. The final formula is a function of Nilson parameter, *G* function, solar zenith angle, leaf area index, background reflectance, and bidirectional reflectance of canopy. This model is useful for accurately calculating FAPAR at a specific time of a day.

We conducted the Monte Carlo simulations to compare the results with the model results when LAI, solar zenith angle, LAD or soil reflectance varies. Results show that the model value approaches the MC value, the error is small and acceptable. It is also shown that we should consider canopy absorption along the outgoing path of photons reflected from the background in order to improve the calculation accuracy.

Field data of wheat is used to validate the algorithm. Results show that the algorithm, the Monte Carlo method, and the field data share the same daily change trend and similar scale, proving the feasibility of the proposed model.

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