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Estimation of fraction of absorbed photosynthetically active radiation from multiple satellite data: Model development and validation

Xin Tao [a,*], Shunlin Liang [a,b], Tao He [a], Huiran Jin [a]

[a] *Department of Geographical Sciences, University of Maryland, College Park, MD 20742, USA*
[b] *State Key Laboratory of Remote Sensing Science, School of Geography, Beijing Normal University, Beijing 100875, China*

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ABSTRACT

The fraction of absorbed photosynthetically active radiation (FAPAR) is a critical input in numerous climatological and ecological models. The targeted accuracy of FAPAR products is 10%, or 0.05, for many applications. However, most of the FAPAR products in current usage have not yet fulfilled the accuracy requirement, thus requiring further improvements. In this study, a new FAPAR estimation model is developed on the basis of the radiative transfer (RT) for a horizontally homogeneous continuous canopy. The spatially explicit parameterization of leaf-scattering and soil background reflectance is derived from a 13-year Moderate Resolution Imaging Spectroradiometer (MODIS) albedo database. The new algorithm requires the input of leaf area index (LAI), which is estimated by a hybrid geometric optical-RT model suitable for both continuous and discrete vegetation canopies in this study. The model calculated radiative surface fluxes, i.e., canopy reflectance, absorption, and transmittance, are compared with the reference data from Radiation transfer Model Intercomparison (RAMI) exercise. The evaluation results show that the model estimated FAPAR has an uncertainty of 0.08 over homogeneous and heterogeneous canopies. The FAPAR estimates from the new model are intercompared with reference satellite FAPAR products and validated with ground-based measurements at the Validation of Land European Remote Sensing Instruments (VALERI) AmeriFlux experimental sites. The validation results show that the FAPAR estimates from the new model are comparable to or slightly better in performance than the MODIS and the Multi-angle Imaging SpectroRadiometer (MISR) FAPAR products when using corresponding satellite LAI product values as the input. The FAPAR estimates are further improved when using the new LAI estimates from the hybrid model as the input. The new model adequately identifies the growing seasons and produces smooth time series curves of estimated FAPAR during a specific duration. The uncertainty is reduced to 0.1 when validating with total FAPAR measurements, and 0.08 when validating with green FAPAR measurements. The improvements are apparent in grasslands and forests with an uncertainty reduction of 0.06. The regional-scale application of the presented model generates consistent FAPAR maps at spatial resolutions of 30 m, 500 m, and 1 km from the Landsat, MODIS, and MISR data, respectively.

1. Introduction

Vegetation plays a key role in the global energy balance, carbon cycle, and water budget of the Earth by controlling the exchanges between the lower atmosphere and the continental biosphere. Vegetation photosynthesis is responsible for the conversion of about 50 PgC yr^{-1} of atmospheric CO_2 into biomass, which represents about 10% of the atmospheric carbon content (Carrer et al., 2013). Land-use changes, mainly attributed to deforestation, have led to an emission level of 1.7 PgC yr^{-1} in the tropics, offsetting by a small amount of uptake of about 0.1 PgC in temperate and boreal areas—thereby producing a net source of around 1.6 PgC yr^{-1} (Houghton, 1995). One of the most important factors to monitor vegetation growth is the distribution of the fraction of absorbed photosynthetically active radiation (FAPAR) within vegetation as it constrains the photosynthesis rate through the energy absorbed by the vegetation. The FAPAR is the fraction of incoming solar radiation in the spectral range from 400 nm to 700 nm that is absorbed by plants (Chen, 1996; Liang et al., 2012; Sellers et al., 1997). As one of the 50 Essential Climate Variables (ECVs) recognized by the UN Global Climate Observing System (GCOS, 2011), FAPAR is a critical input parameter in the biogeophysical and biogeochemical processes described by numerous climatological and ecological models, such as the Community Land Model, the Community Earth System Model, and crop growth models (Bonan et al., 2002; Kaminski et al., 2012; Maselli et al., 2008; Tian et al., 2004). The Moderate Resolution Imaging Spectroradiometer (MODIS) FAPAR product (MOD15) is a critical input for MODIS evapotranspiration (MOD16), in addition to gross (GPP) and net primary production (NPP) products (MOD17) (Liang et al., 2012). A 10% increase in FAPAR would result in equal amounts of

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[*] Corresponding author.
E-mail address: xtao@umd.edu (X. Tao).

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GPP, NPP, and carbon sink increases. Hall et al. (2006) conducted sensitivity analysis and determined that NPP is largely driven by FAPAR in the Carnegie Ames Stanford Approach (CASA) model, with weaker effects from the lower variability of PAR and lower sensitivity to temperature and precipitation.

Despite the existence of the aforementioned numbers, the spatial distributions of carbon sources and sinks remain a core question and a subject of debate for the broad scientific community. In this regard, an improved representation of vegetation status in the ecological modeling is desirable. The reliable estimates of GPP, NPP, and carbon flux depend on high FAPAR input accuracy. An accuracy of ±0.05, or relative accuracy of 10%, in FAPAR is considered acceptable to describe the vegetation properties precisely and can be effectively applied in agronomical and other applications (GCOS, 2011).

FAPAR can be derived from ground measurements, although the point-scale ground measurements are insufficient for regional or global coverage (Li et al., 1995). Satellite sensors efficiently acquire land surface information at regional and global scales, representing new opportunities for monitoring biophysical parameters (Asner et al., 1998). The estimation of FAPAR from optical remote sensing is based on physical models or empirical relationships (Liang, 2007). Empirical relationships between FAPAR and observations or derivatives from observations are established without knowledge of the underlying physical mechanism in the radiative transfer (RT) process. Therefore, simplicity is the primary advantage (Gobron et al., 1999). However, no unique relationship between FAPAR and the vegetation index is universally applicable to all conditions because canopy reflectance is also dependent on other factors such as geometrical measurement and spatial resolution (Asrar et al., 1992; Friedl, 1997). Moreover, the relationship between FAPAR and the vegetation index such as the normalized difference vegetation index (NDVI) is quite sensitive to the reflectance of background material (Asrar et al., 1992). Physical models analyze the interactions between solar radiation and vegetation canopies and reveal cause–effect relationships (Pinty et al., 2011; Widlowski et al., 2007). They are generally applicable to most conditions including over different land covers and during different time periods, although they require complex parameterizations. This study focuses on improving FAPAR accuracy under various conditions, and thus chooses to develop physical models.

Physical models for the retrieval of biophysical characteristics from reflected radiation of canopy can be divided into several classes (Liang, 2004): RT, geometric-optical, hybrid, and Monte Carlo, in addition to other computer simulations. The pure geometric-optical model considers only single scattering within the canopy, whereas an RT model also includes multiple scattering. Monte Carlo models and computer simulations are based on RT principles but are executed following random events rather than explicit formulae, and therefore are computationally intensive. They may be used as surrogate truths to evaluate other RT and geometric-optical models (Widlowski, 2010; Widlowski et al., 2007). An RT model is developed to calculate FAPAR in this study because of its theoretically high accuracy by including both single and multiple scattering and efficiency by following the explicit formulae.

In addition to the retrieval model performance, the determinants of FAPAR accuracy can be traced to the accuracy of such input parameter as leaf area index (LAI), soil background reflectance, and fractional canopy cover. LAI is one of the most important parameters in the determination of FAPAR, and its accuracy directly influences that of FAPAR. A 10% change in tree LAI could account for a 55% change in FAPAR (Asner et al., 1998). The collection of soil background reflectance is important for guaranteeing that the simulated reflectance can cover the entire set of observed surface reflectance data (Fang et al., 2012; Knyazikhin et al., 1998b; Shabanov et al., 2005). Otherwise, saturation of the relationship between FAPAR and surface reflectance may occur; very high FAPAR values are not reliable (Weiss et al., 2007). The correct estimation of FAPAR also relies on that of fractional canopy cover, the underestimation of which might cause unrealistically high FAPAR values (Kanniah et al., 2009). In addition to the development of new FAPAR retrieval models suitable for various land-cover types, this study also aims at improving the accuracy of FAPAR estimates by using more accurate model inputs such as LAI and soil background and leaf-scattering albedos (Xiao et al., 2015b). The LAI is calculated by using a hybrid geometric-optic RT model considering the shadowing and multiple scattering in the canopy (Tao et al., 2009; Xu et al., 2009). The soil background and leaf-scattering albedo are generated from long time series of surface anisotropy products (He et al., 2015; Tao et al., 2013). The FAPAR estimates from this study is green FAPAR considering both direct and diffuse radiation, which are validated with in-situ green and total FAPAR measurements (Tao et al., 2015).

The direct validation of satellite FAPAR products with ground measurements has generated some encouraging results, particularly when compared with previous versions of FAPAR products. The MODIS Collection 4 FAPAR product has been validated with ground measurements to demonstrate an accuracy of 0.2 (Baret et al., 2007; Fensholt et al., 2004; Huemmrich et al., 2005; Olofsson and Eklundh, 2007; Steinberg et al., 2006; Turner et al., 2005; Weiss et al., 2007; Yang et al., 2006), and the MODIS Collection 5 FAPAR product presents an improved accuracy to around 0.1 (Baret et al., 2013; Camacho et al., 2013; Martinez et al., 2013; McCallum et al., 2010; Pickett-Heaps et al., 2014; Xiao et al., 2015a). This improvement could be the result of a new stochastic RT model, which adequately captures the 3D effects of foliage clumping and species mixtures of natural ecosystems (Kanniah et al., 2009). The Multi-angle Imaging SpectroRadiometer (MISR) FAPAR product exhibits performance similar to that of the MODIS C5 FAPAR product. However, the MODIS and MISR FAPAR products might show overestimation at certain sites. For example, Martinez et al. (2013) reported that MODIS tends to provide high values in cultivated areas and Mediterranean forests, such as the Puechabon. The MODIS FAPAR product may also have positive bias for very low FAPAR values. A similar overestimation problem has been detected in MISR FAPAR data, with a positive bias as large as 0.16 in broadleaf forests (Hu et al., 2007). In addition to the overestimation problem, underestimations have been detected in the MODIS Collection 4 FAPAR product for certain sites in Switzerland (Olofsson and Eklundh, 2007). Overall, the current FAPAR products are close to, but have not fulfilled, the accuracy requirement, and further improvements are still needed (Tao et al., 2015).

This study tests how well the FAPAR accuracy can be improved from multiple satellite surface reflectance products with a new model and more accurate model inputs. Section 2 introduces data for FAPAR estimation and validation, and Section 3 describes a new model for FAPAR retrieval. The FAPAR estimates from this new model are compared with reference data and validated with in-situ measurements at the site scale in Section 4, and the model is applied to multiple resolution images at the regional scale in Section 5. Section 6 offers a discussion of the findings and conclusions.

2. Data

The data used in this study include satellite surface reflectance data, FAPAR products derived from MODIS and MISR, and FAPAR in-situ measurements from two groups of experimental sites.

2.1. Satellite surface reflectance

The MODIS, MISR, Landsat Thematic Mapper (TM), and Enhanced Thematic Mapper Plus (ETM+) reflectance data are used for FAPAR estimation. Satellite surface reflectance products for FAPAR retrieval are listed in Table 1. Different spatial resolutions of FAPAR estimates can induce the scaling effect of FAPAR, which occurs when the surface is heterogeneous and the retrieval algorithm is nonlinear (Tao et al., 2009; Xu et al., 2009). Because of the scale difference, the validation results at more homogeneous sites are expected to have a higher FAPAR accuracy. We evaluate the heterogeneity around the validation sites as described