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# Sensitivity analysis of retrieving fraction of absorbed photosynthetically active radiation (FPAR) using remote sensing data

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ABSTRACT

The fraction of absorbed photosynthetically active radiation (FPAR) is a key biophysical variable for vegetation productivity estimation, vegetation growth condition monitoring, and climate change analysis. The object of this study is to conduct a comprehensive sensitivity analysis on the contributing factors of FPAR variation, in order to reveal the impacts of the interference factors on FPAR estimation using remote sensing and to improve the accuracy of the model. The analysis was conducted based on a coupled leaf-canopy–atmosphere radiative transfer model and a global sensitivity analysis algorithm. Due to the impact of diffuse FPAR on the variation of FPAR, we also analyzed the determinant factors of diffuse FPAR. The results showed that leaf area index (LAI) and the average leaf inclination angle (ALA) are two important canopy structural parameters determining FPAR variability, especially before canopy closure. FPAR was found to be affected differently by these two variables with canopy development. Canopy background reflectance has a great impact on FPAR estimation at low LAI values (LAI < 1.0). For the effects of leaf biochemical variables, the contribution of leaf chlorophyll concentration (LCC) to FPAR variability is negligible at the early vegetative growth stage, but becomes dominant starting from the exuberant growth periods, with the contribution increasing consistently with LAI. For the external factors, solar zenith angle (SZA) and aerosol optical depth (AOD) are two important driving factors significantly influencing FPAR by changing the optical path length and the proportion of the diffuse photosynthetically active radiation (PAR). SZA influences both FPAR and diffuse FPAR throughout the growing period, while, AOD is the most important determinant factor for diffuse FPAR variation. When LAI is low, the impact of canopy background reflectance on the diffuse FPAR cannot be ignored. The analysis also revealed that the diffuse FPAR variation significantly influences on the vegetation productivity estimation. In summary, this study shows that the variation of FPAR is affected by different factors in different ways. It provides a comprehensive understanding of the contributing factors to FPAR variability including the diffuse FPAR, which could be potentially useful in developing FPAR retrieval algorithm from remote sensing data.



## 1. Introduction

The fraction of absorbed photosynthetically active radiation (FPAR), defined as the fraction of photosynthetically active radiation (PAR) absorbed by a green canopy in the 0.4–0.7 μm spectral range, is well known as an important biophysical variable in characterizing energy, mass, and momentum exchanges between phytosphere and atmosphere [1]. It is a key input parameter in most current productivity efficiency models (PEMs) based on the light use efficiency theory for assessing vegetation productivity (e.g., net primary productivity (NPP) and gross primary productivity (GPP)) [2–5]; it is also widely used to monitor crop growth status, drought conditions, land use variation and vegetation dynamics (e.g., phenology) [6]. Due to its importance, FPAR has been identified as one of the fundamentally essential climate variables (ECVs) by the Global Terrestrial Observing System (GTOS) and the Global Climate Observing System (GCOS) [1]. Satellite observation is recognized as the only way to obtain FPAR with spatial–temporal variation at the regional or global scale. Many kinds of methods had been developed and validated based on optical remote sensing, and they can be categorized into the empirical approaches based on vegetation indices and the physical approaches using canopy reflectance model inversion [7]. The empirical approach is popularly employed in most regional scale studies because vegetation indices are treated as a proxy of FPAR at most growth stages. As the canopy reflectance model can clearly explain the relationship between the canopy and light absorption, the physical model has a robust ability for FPAR estimation at the global scale [7]. However, most of the current algorithms were only applied under the clear sky condition as the quality of optical satellite data is significantly affected by diffuse radiation conditions such as

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overcast, haze and aerosol optical depth (AOD). In recent years, the effects of diffuse radiation on vegetation conditions, vegetation productivity, and global climate change have increasingly attracted scientists' attention [4,8–13]. A great number of studies pointed out that the increasing fraction of diffuse radiation could improve the light use efficiency (LUE) [5,12,14], although the total photosynthetically active radiation (PAR) reaching to the top of canopy decreased. Many studies have found that the trend of total radiation has declined, while the fraction of diffuse radiation increased in different regions of the world in the past few years. For example, a significant decreasing trend of total radiation in the recent 50 years in China was reported by Zhu et al. [15]. This result is very important for global climate change studies among the atmospheric, water and vegetation cycle, especially for the accuracy of carbon budget estimation [4,10–13].

According to the effects of radiation and diffuse radiation on vegetation productivity, FPAR can also be divided into direct FPAR ($FPAR_{dir}$) and diffuse FPAR ($FPAR_{dif}$) as it represents the summed canopy absorbed efficiency from both direct and diffuse PAR [16,17]. However, daily FPAR in most current satellite-derived FPAR algorithms is defined as the instantaneous black-sky FPAR at solar noon [18] and neglects the effect of diffuse radiation [7]. This is one of the possible reasons for the uncertainties in FPAR and vegetation productivity estimation using satellite data [4,7]. To further the understanding about the physical characteristics of FPAR and improve the accuracy of FPAR estimation based on satellite observation, a comprehensive sensitivity analysis about the effects of atmospheric factors, canopy structural parameters and soil environment on FPAR variation is both important and necessary.

Several sensitivity analyses had been conducted in literature to assess the contributions of driving factors on FPAR variation at different scales. Asner and Wessman [19] employed the geometrical optical radiative transfer model to assess the driving factors on FPAR variation from the views of landscape, canopy and leaf scale. The results showed that the effect of landscape was more significant on FPAR than that of the leaf area index (LAI) at the landscape scale, while LAI played a more significant role in FPAR than leaf biochemical variables at the canopy scale. Li et al. [16] conducted a FPAR sensitivity analysis based on the PROSAIL model and found that both FPAR and $FPAR_{dif}$ at early growing stage were more affected by the effect of leaf angle distribution (LAD), LAI and solar zenith angle (SZA) than that at other growing stages. The studies conducted by Qi [20] and Cristiano et al. [21] emphasized the effects of canopy structure (e.g., LAD) on FPAR variation based on canopy reflectance model and field measurements. The results showed that the total reflected PAR from a canopy with a planophile (horizontal) LAD was always higher than that from a canopy with an erectophile (vertical) LAD; hence the FPAR in planophile canopy was less than that of erectophile canopy. Gao et al. [22] pointed out that leaf chlorophyll content (LCC) played the most important role in FPAR variation at the leaf scale. All these results are useful for further understanding the physical characteristics of FPAR and for developing algorithms for improved FPAR estimation accuracy. However, there are two limitations in these FPAR sensitivity analyses. Firstly, most studies focused on the effects of canopy structure (e.g., LAI and LAD) and physiological variables (e.g., LCC) on FPAR variation, and neglected the effects of atmospheric conditions; secondly, there is a limitation in the methods used for sensitivity analysis, which lead to some uncertainties in the analysis results. Most FPAR sensitivity analyses were conducted by a local sensitivity method that is a simple and effective method. However, the local sensitivity method is based on the assumption that one of the inputs varies while the other inputs are invariant. It is difficult to reveal the effects of interactions among the input variables on the targeting variable. The global sensitivity analysis methods have been developed to overcome this limitation and become popular in the sensitivity analysis of an ecological model. The main characteristic of this approach is that all inputs are varied simultaneously over the entire input space, and the contributions on the outcome of both individual inputs and interactions among inputs are assessed [23].

In this study, a coupled atmospheric–canopy radiative transfer model based on the MODerate resolution atmospheric TRANsmission (MODTRAN) model [24], Scattering by Arbitrarily Inclined Leaves Model (SAIL) [25], and Leaf Optical Properties Spectra (PROSPECT) [25,26] was employed to calculate FPAR and simulate top of canopy (TOC) reflectance. The objective of this study is to comprehensively invert the responses of FPAR and $FPAR_{dif}$ to the variables based on the coupled model under different atmospheric environmental conditions, canopy structural and leaf biochemical variables, respectively.

## 2. Model and methods

### 2.1. The coupled leaf-canopy–atmospheric radiative transfer model

The PROSAIL model [25], a combination of the PROSPECT leaf optical properties model and the 4SAIL canopy bidirectional reflectance model, is widely employed to simulate canopy reflectance for a range of biochemical and biophysical variables. The PROSPECT model, developed based on the generalized plate model from Allen et al. [27], is a simple yet effective leaf radiative transfer model to simulate leaf spectral reflectance and transmittance from the 400 to 2500 nm spectral range [25,26]. Six parameters are required in the latest version of PROSPECT (PROSPECT-5) [26] including the leaf mesophyll structure parameter (Ns), the leaf chlorophyll a and b content (Cab), the leaf equivalent water thickness (Cw), the dry matter content (Cm), the leaf brown pigment content (Cbr), and the carotenoid content (Car). The 4SAIL model is a 1D turbid medium model for canopy reflectance simulation based on the four-stream approximation of the radiative transfer equation [25,28]. The hotspot effect was considered and adapted in the revised model (SAILH) by Kuusk [29]. In the 4SAIL model, the TOC bidirectional reflectance is simulated as a function of the canopy parameters and the external parameters. For the canopy parameters, they are LAI, average leaf angle (ALA), hotspot parameter (hotspot) and soil brightness parameter (psoil), respectively. For the external parameters, they are the fraction of diffused incoming solar radiation (skyl) and the geometry parameters including the sun zenith angle (SZA), the sensor zenith angles (VZA) and the azimuth angle between the sun and the sensor (RAA), respectively. The skyl is an environmental parameter related to atmospheric condition and is calculated as the ratio between diffuse and total incoming radiation. The radiance can be successfully simulated by the atmospheric radiative transfer models, such as MODTRAN. MODTRAN was developed based on the LOW resolution TRANsmittance 7 (LOWTRAN 7) model [24]. It is well known for modeling scattering and absorption effect under different atmospheric scenarios with high accuracy and high spectral resolution up to 1 $cm^{-1}$, and has been successfully applied to both at-sensor radiance for atmospheric correction and radiation simulations [24].

Fig. 1 shows the flowchart of the coupled atmosphere–canopy model. The skyl is a connection factor to combine the PROSAIL and the MODTRAN models. In the first step, both leaf spectral reflectance and transmittance are simulated by the PROSPECT-5 for a range of leaf parameters including Cab, Cw,Cm and Ns. Secondly, the total radiation and diffuse radiation are calculated by MODTRAN for a range of atmospheric parameters including AOD, precipitable water (PW) and Ozone ($O_3$), and geometry parameters (e.g., sun zenith angle (SZA), view zenith angle (VZA), and relative azimuth angle (RAA)). The bidirectional canopy reflectance, FPAR and $FPAR_{dif}$ are finally simulated by the 4SAIL with the simulated leaf spectral reflectance and transmittance, skyl, LAI, ALA, soil reflectance, and the geometry parameters.

### 2.2. FPAR calculation

FPAR is the fraction of PAR absorbed by a green canopy [7,30], and the law of conservation of energy is useful for deriving FPAR from PROSAIL simulation. In this study, both FPAR and $FPAR_{dif}$ are resolved from PROSAIL simulations using the Four-Stream Radiative Transfer theory developed by Verhoef and Bach [30]. To obtain the absorption efficiency by