

A PHYSICAL INVERSION METHOD OF CANOPY FPAR FROM AIRBORNE LIDAR DATA AND GROUND MEASUREMENTS

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ABSTRACT:

Fraction of absorbed Photosynthetically Active Radiation (FPAR) is one of the pivotal parameters in terrestrial ecosystem modelling and crop growth monitoring. Airborne LiDAR is an advanced active remote sensing technology which can acquire fine three-dimensional canopy structural information quickly and accurately. Although some previous studies have shown that LiDAR-derived metrics had strong relationships with canopy FPARs, these estimation models without physical meaning are hard to be extended to various vegetation canopies and different growth periods. This study proposed a physical FPAR inversion method based on airborne LiDAR data and field measurements. The method considered direct and diffuse radiations separately based on the SAIL model and energy budget balance principle. The canopy FPAR was inverted from the structural information provided by LiDAR point cloud data and the spectral information provided by ground measurements. The estimated FPAR was validated with the field-measured FPAR over 39 maize plots. Results showed that the proposed method had a good performance in estimating the total FPAR of maize canopy ($R^2 = 0.76$, RMSE = 0.062, $n = 39$). This study provides the potential to estimate the total, direct, and diffuse FPARs of vegetation canopy from airborne LiDAR data.

1. INTRODUCTION

The Fraction of absorbed Photosynthetically Active Radiation (FPAR) is defined as the ratio of Absorbed Photosynthetically Active Radiation (APAR) by the green component of vegetation to total incoming Photosynthetically Active Radiation (PAR) in 400-700nm spectrum (Zhu et al., 2013). It manifested the capability of vegetation canopy to exchange mass and energy with the outside environment, thus being one of the key parameters in crop yield modelling and terrestrial ecosystem modelling (Huemmrich et al., 2019). Remote sensing (RS) inversion has proven an effective way to estimate the canopy FPAR over large areas. Numerous researches have applied the passive optical remote sensing for canopy FPAR inversions by establishing the empirical, semi-empirical, or physical relationships between FPAR and vegetation indices (VIs), e.g., normalized difference vegetation index (NDVI), simple ratio index (SRI), and carotenoid reflectance index (CRI) (Fensholt et al., 2004; Li and Fang, 2014; Majasalmi et al., 2014). However, the saturation of vegetation indices limits the estimation accuracy of canopy FPAR in dense canopies (Tan et al., 2014). Additionally, the optical imagery cannot provide the canopy vertical structural information but only spectral properties and horizontal distribution.

Airborne LiDAR is an advanced active remote sensing technique which is capable of capturing fine three-dimensional structural features of vegetation canopy (Wulder et al., 2012). High-intensity laser pulse penetrating into vegetation canopy promotes that the received signals have the capability to

characterize the light transmittance and absorption of the canopy. To date, some previous studies have attempted to use the airborne LiDAR to estimate canopy FPAR based on the empirical relationships with LiDAR-derived metrics (Chasmer et al., 2008; Luo et al., 2014; Thomas et al., 2006). Luo et al. (2014) derived the canopy FPAR by building the linear regression model between the LiDAR-derived fractional cover and the field-measured FPAR. Qin et al. (2018) estimated the FPAR of maize canopy from the multiple linear regression model based on airborne LiDAR height and coverage metrics. However, these empirical or semi-empirical models without physical meaning are difficult to be universally applied to varying vegetation canopies and different growth periods. In addition, although the airborne LiDAR provides detailed spatial three-dimensional structure, it is impossible to physically retrieve the canopy FPAR in a spectrum range due to the limitation of single wavelength design. The spectral characteristics of canopy and ground must be considered in the canopy FPAR inversions. The spectral information could be obtained by field measurements or multispectral, hyperspectral remote sensing imagery.

Therefore, the objective of this paper is to propose a physical FPAR inversion model based on airborne LiDAR data. The ground-measured spectrum was used as auxiliary data to provide the spectral properties of canopy and ground. To further verify the validity of the inversion model, we implemented the inversion experiments of maize canopy FPAR. The inversion

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results were validated by field measurements to evaluate the estimation accuracy of the model.

2. METHODOLOGY

2.1 Background Theory

FPAR is the summed canopy absorption efficiency for the total PAR (including direct and diffuse PARs). Hence, the total APAR of vegetation canopy is composed of the direct and diffuse APARs, as in Eq. (1). Direct and diffuse FPARs are defined as the absorbed proportion of canopy to direct and diffuse incident PARs, respectively, as in Eq. (2) and (3).

$$APAR_{total} = APAR_{dir} + APAR_{diff} \quad (1)$$

$$APAR_{dir} = PAR_{dir} \cdot FPAR_{dir} \quad (2)$$

$$APAR_{diff} = PAR_{diff} \cdot FPAR_{diff} \quad (3)$$

$$skyl = \frac{PAR_{diff}}{PAR_{total}} = \frac{PAR_{diff}}{PAR_{dir} + PAR_{diff}} \quad (4)$$

where $APAR_{total}$, $APAR_{dir}$, $APAR_{diff}$ = total, direct, and diffuse APARs,

PAR_{total} , PAR_{dir} , PAR_{diff} = total, direct and diffuse incident PARs,

$FPAR_{dir}$, $FPAR_{diff}$ = direct and diffuse FPARs,

$skyl$ = the proportion of diffuse PAR in total incident PAR.

By summarizing Eq. (1)-(4), the total FPAR of vegetation canopy is calculated as the weighted sum of direct and diffuse FPARs (Li and Fang, 2014), as in Eq. (5).

$$FPAR = \frac{APAR_{total}}{PAR_{total}} = (1 - skyl) \cdot FPAR_{dir} + skyl \cdot FPAR_{diff} \quad (5)$$

2.2 FPAR Inversion Model

In line with the energy budget balance principle, the incoming radiation is partly absorbed by the vegetation canopy, partly absorbed by the soil and rest returned to the top of canopy (Li et al., 2015). Based on Eq. (5), we considered the direct and diffuse radiations separately.

For each radiation, the incident energy corresponds to the portion irradiated to the vegetation and the portion irradiated to the soil. Gap fraction describes the probability of incident direct radiation to the soil. Canopy openness is defined as the proportion of radiation scattered by the soil to the top of crown. The absorbed proportions of soil to different incident radiations are related to the reflectances of sunlit and shadowed soils, respectively. Hence, the direct and diffuse FPARs can be calculated by 1 minus the direct or diffuse canopy reflectivity, then minus the product of the probability of incident radiation to the soil and the direct or diffuse soil absorptivity, as in Eq. (6) and (7). The detailed light absorption and propagation process in the vegetation canopy is shown in Figure 1.

$$FPAR_{dir} = 1 - \rho_{dir} - P_{gap} \cdot (1 - \rho_{s_{dir}}) \quad (6)$$

$$FPAR_{diff} = 1 - \rho_{diff} - K_{open} \cdot (1 - \rho_{s_{diff}}) \quad (7)$$

where ρ_{dir} , ρ_{diff} = the proportions of the direct, diffuse radiations reflected by land scene to the incident direct, diffuse radiations, respectively,

$\rho_{s_{dir}}$, $\rho_{s_{diff}}$ = the reflectivities of sunlit and shadowed soils, respectively,

P_{gap} = canopy gap fraction,

K_{open} = canopy openness.

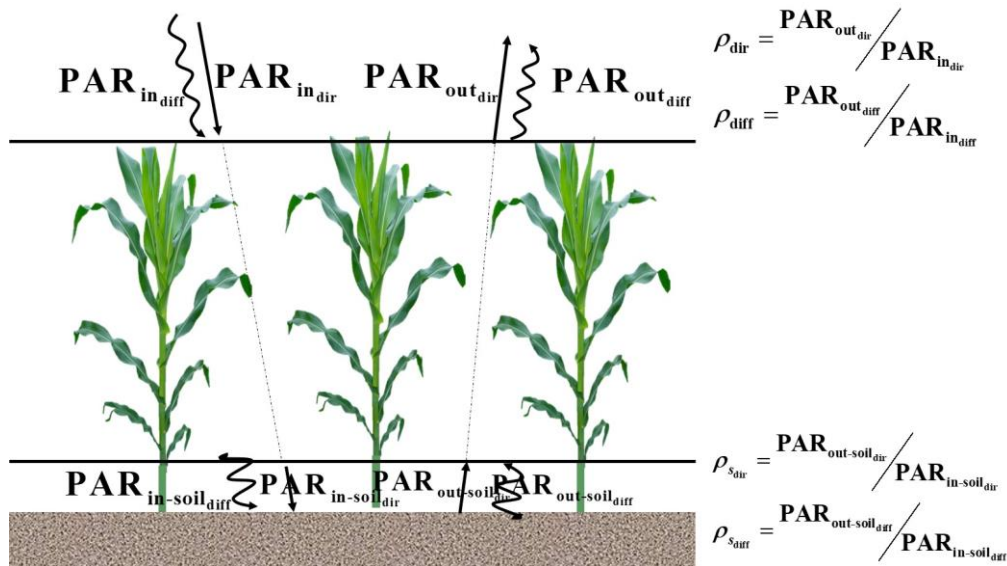


Figure 1. The process of light absorption and propagation in the canopy. PAR_{in_dir} and PAR_{in_diff} are the direct and diffuse above-canopy downwelling incident PARs. PAR_{out_dir} and PAR_{out_diff} are the direct and diffuse above-canopy upwelling excitant PARs.

$PAR_{in_soil_dir}$ and $PAR_{in_soil_diff}$ are the direct and diffuse below-canopy downwelling incident PARs. $PAR_{out_soil_dir}$ and $PAR_{out_soil_diff}$ are the direct and diffuse below-canopy upwelling excitant PARs.

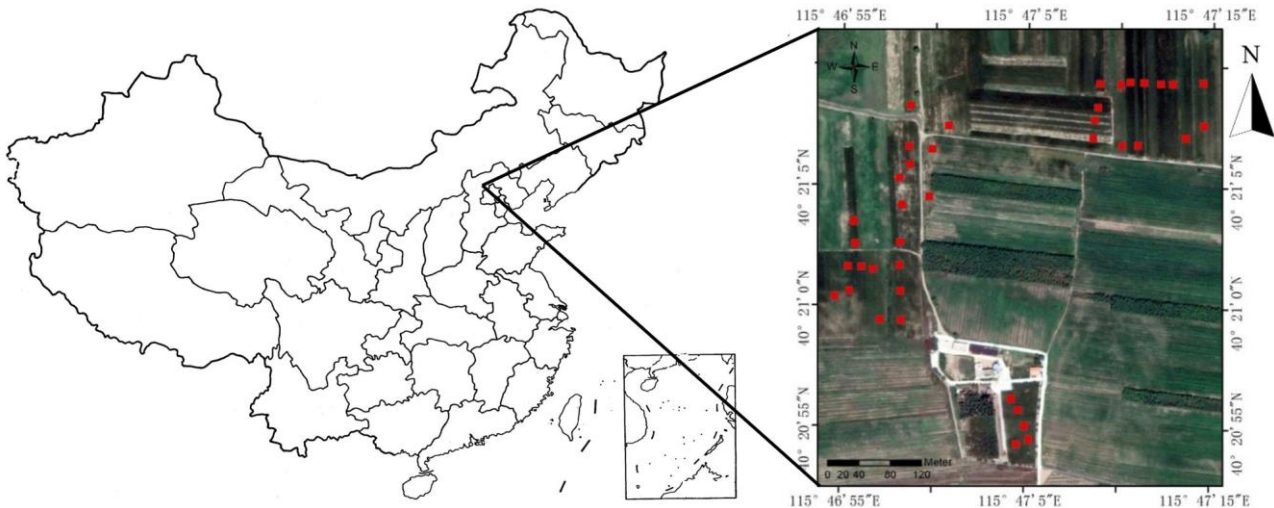


Figure 3. Study area and sampling plots

By substituting Eq. (6) and (7) into Eq. (5), the total FPAR is expressed as in Eq. (8).

$$\text{FPAR} = 1 - \text{scene albedo} - [(1 - \text{skyl}) \cdot P_{\text{gap}} \cdot (1 - \rho_{\text{dir}}) + \text{skyl} \cdot K_{\text{open}} \cdot (1 - \rho_{\text{diff}})] \quad (8)$$

where $\text{scene albedo} = (1 - \text{skyl}) \cdot \rho_{\text{dir}} + \text{skyl} \cdot \rho_{\text{diff}}$.

Considering the spectral variation, the total canopy FPAR is an integral over 400 - 700nm spectral domain (Xie et al., 2010), as in Eq. (9).

$$\text{FPAR} = \int_{400 \text{ nm}}^{700 \text{ nm}} \text{FPAR}_{\lambda} d\lambda = \frac{1}{300} \sum_{\lambda=400}^{700} \text{FPAR}_{\lambda} \Delta\lambda \quad (9)$$

where $\text{FPAR}_{\lambda} = \text{FPAR}$ at wavelength λ .

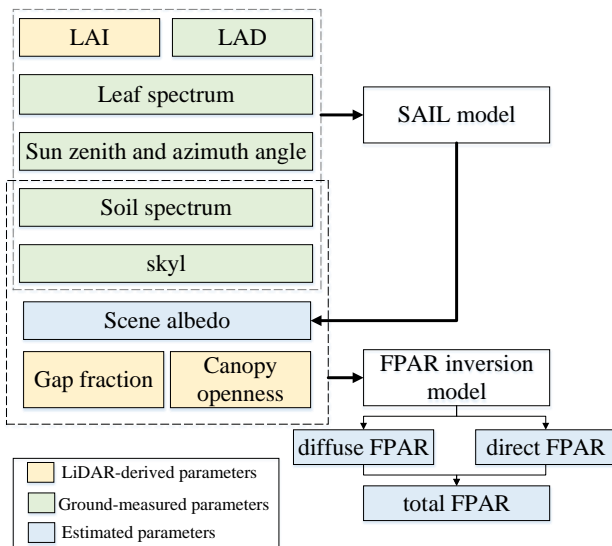


Figure 2. Schematic scheme of FPAR inversion model

From Eq. (8), it is seen that FPAR is a parameter related to vegetation structure, vegetation spectrum, soil spectrum and skylight environment. In this study, we used the SAIL model (Verhoef, 1984) to simulate the scene albedo in 400-700 nm based on the lidar-derived structural parameters and field-measured spectrums. Then the total FPAR of vegetation canopy

is estimated by using Eq. (8) and (9). The detailed scheme of FPAR inversion model is shown in Figure 2.

2.3 Study Site and Field Measurements

The study area is located in Zhangjiakou, northeast China (40°20'N-40°22'N, 115°46'E-115°48'E) (Figure 3), where the maize is the dominant crop. Airborne LiDAR point cloud data were acquired by Riegl LiDAR VUX-1 system on July 21, 2019. 39 plots with the size of 10*10 m² were randomly selected for *in-situ* measurements. The leaf and soil spectrums were recorded by the Analytical Spectral Devices (ASD). The solar observation direction and cloud cover were recorded by manual judgments. The four PARs in each plot were measured by the LI-191SA linear optical quantum sensor (Gower et al., 1999), and then the field-measured FPARs were calculated according to Eq. (10).

$$\text{FPAR} = \frac{(\text{PAR}_{\text{ad}} - \text{PAR}_{\text{au}}) - (\text{PAR}_{\text{bd}} - \text{PAR}_{\text{bu}})}{\text{PAR}_{\text{ad}}} \quad (10)$$

where PAR_{ad} , PAR_{au} = downwelling and upwelling PAR above the canopy, respectively;

PAR_{bd} , PAR_{bu} = downwelling and upwelling PAR below the canopy, respectively.

2.4 LiDAR Data Processing

First, the raw lidar point cloud data is denoised by the nearest neighbour algorithm to remove outliers. Then the denoised point cloud is classified into vegetation and ground points using the progressive triangulated irregular network (TIN) filter algorithm. By counting the number of ground points and vegetation points, the gap fraction (P_{gap}) and leaf area index (LAI) of each plot can be calculated, as in Eq. (11) and (12). Based on Eq. (13), the lidar-derived canopy openness is simply calculated by the weighted average of gap fraction at zenith angles from 10° to 60° with 5° interval.

$$P_{\text{gap}} = \frac{N_g}{N_g + N_v} \quad (11)$$

$$\text{LAI} = -\frac{1}{k} \ln P_{\text{gap}} \quad (12)$$

$$K_{\text{open}} = \int_0^{\pi} P_{\text{gap}}(\theta) \sin 2\theta d\theta \quad (13)$$

where N_g, N_v = the number of ground points and vegetation points in each plot, respectively,

k = projection coefficient, related to leaf angle distribution.

θ = zenith angle.

2.5 Accuracy Assessment

The FPARs of maize canopy estimated by the proposed inversion model are compared with the field-measured FPARs over 39 plots in this study. The inversion accuracy is assessed based on the coefficient of determination (R^2), root mean squared error (RMSE), and bias error.

3. EXPERIMENTAL RESULTS

Figure 4 displayed the scatterplot of the estimated FPARs versus the field-measured FPARs. The regression result showed that there was a strong correlation between the predicted value and the true value ($R^2 = 0.76$, RMSE = 0.062, bias error = -0.098, $n = 39$). This indicated that the inversion method proposed in this study had a reliable estimation accuracy of canopy FPAR. The estimation bias might be related to inaccurate canopy openness caused by limited airborne scanning angle.

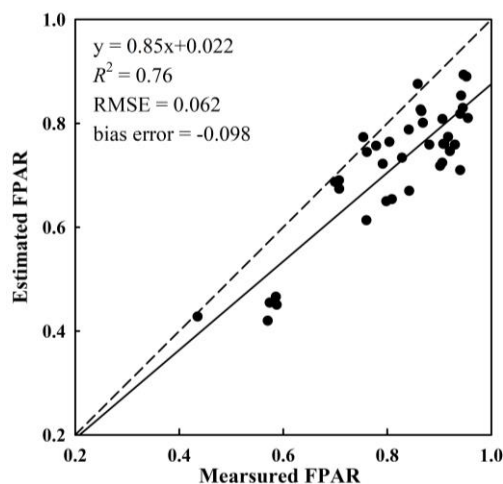


Figure 4. Comparison of the estimated FPAR and the field-measured FPAR ($n = 39$)

4. CONCLUSIONS

This study proposed a physical inversion model of canopy FPAR based on airborne LiDAR data and ground measurements. The inversion model considered the direct and diffuse radiations separately by combining the energy budget balance principle and SAIL model. We performed this FPAR inversion model on the maize canopies over 39 plots, and then validated the inversion results with the field-measured FPARs. Results indicated that the proposed model achieved the FPAR estimation of maize canopy accurately ($R^2 = 0.76$, RMSE = 0.062, $n = 39$). However, due to the lack of field measurements, some intermediate results of the inversion model cannot be verified, such as surface albedo, direct and diffuse FPARs. A future study is necessary to validate the estimation accuracies of direct and diffuse FPARs. In addition, further work is required to replace the ground spectrum measurements by multispectral

or hyperspectral imagery and then estimate the canopy FPAR by combining the LiDAR and passive optical remote sensing.

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