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Research Article

Experimental Evaluation of Wheat Biophysical Variables Retrieval from Sentinel-2 MSI through Inversion of Radiative Transfer Model

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ABSTRACT

Present study attempted to assess the retrieval of biophysical parameters from in-situ spectroradiometric observations equivalent to broadband Sentinel-2 MSI reflectances. These broadband reflectances were used to retrieve three biophysical parameter viz., leaf chlorophyll content (Cab), equivalent water thickness (EWT) and leaf area index (LAI) of wheat under different treatments of research farm study. The accuracy of biophysical parameters retrieval through inversion of PROSAIL model using LUT approach followed the order of LAI > Cab>EWT. The retrieved Cab showed poor agreement with observed Cab. The results showed the inadequacy or failure of LUT inversion approach for EWT retrieval due to narrow range of variation in EWT. Thus, the PROSAIL model can be used successfully for retrieval of LAI, but require its further improvements for retrieval of Cab and EWT.

Key words: Crop, PROSAIL, Chlorophyll, Equivalent water thickness, Leaf area index

Introduction

Quantitative retrieval of biophysical and biochemical variables is a requirement in a range of agricultural and environmental applications (Chakraborty *et al.,* 2015, 2018; Sehgal *et al.,* 2016). Among all biophysical variables, leaf area index (LAI), leaf chlorophyll content (LCC) and equivalent water thickness of a vegetation are most important (Houborg *et al.,* 2008). Recent advancement in satellite remote sensing offers the possibility of accurate estimation of biophysical variables at different temporal and spatial scales (Vohland *et al.,* 2010). Biophysical variables retrieval from remote sensing data are classified in two categories (a) Statistical and (b) Physical. Statistical methods suffer from limitation of sensor and site specificity, are supposed to change in space and time (Meroni *et al.*, 2004). Whereas, physical methods are based on radiative transfer theory which are able to mimic spectral variation of canopy reflectance as a function of canopy, leaf and soil background characteristics (Goel, 1989; Meroni *et al*., 2004). Among the canopy radiative transfer models (RTMs), PROSAIL model is most widely used for biophysical variable retrieval of agricultural crops (Jacquemoud *et al.,* 2009). Various strategies have been employed to invert RTMs include Support Vector Machine (Camps-Valls *et al*., 2009), Genetic Algorithms (Mridha *et al.,* 2015), Artificial Neural Networks (Chakraborty *et al.,* 2015), Look-up-table (Sehgal *et al.,* 2016) etc. Look-up-table approach was employed in this study due to certain advantages over the other approaches (Kimes *et al.,* 2000; Houborg *et al*., 2008).

Increasing availability of high resolution satellite data in public domain now a days paved the way for more accurate estimation of canopy

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biophysical variables in different spatial extent. Among the available satellite data, Landsat-8 Operational Land Imager from NASA and Sentinel-2 MSI from European Space Agency provides the high spatial resolution remote sensing dataset. But, application of plant biophysical parameter retrieval from MSI sensors are limited. In this study, a field experiment was conducted to examine the retrieval of biophysical variables such as LAI, LCC and EWT through PROSAIL inversion using broadband reflectances of Landsat-8 OLI and Sentinel-2 MSI from spectroradiometric observations taken over wheat canopy.

Materials and methods

Study area

A field experiment was conducted in the experimental farm (Main Block 4C) of Division of Agricultural Physics, Indian Agricultural Research Institute, New Delhi, located at 28°38′23″ North latitude and 77°09′27″ East longitude with altitude of 228.6 meter above mean sea level. The climate is subtropical and semiarid characterized by hot dry summer and cold winter. The mean monthly maximum temperature in the *rabi* season (November to April) ranges from 20 to 36°C and mean monthly minimum temperature from 6 to 19°C. Mean annual rainfall (30 years average) is 769.3 mm, of which 75% is received during the south west monsoon season between July to September and very little rain is received in *rabi* season.

Experimental details

The area of experimental site was 540 m^2, out of which net sown area was 360 m^2. Experiment was laid out as split plot design, in which each plot has size of 5×4 m^2 with sufficient margins for irrigation channels and bunds. Soils of the site are deep, well drained and sandy loam in texture throughout the profile. Wheat (cv. HD 2967) was raised during the *rabi* season of 2015-2016 and 2016-17 in split plot design with irrigation as main treatment and date of sowing as sub plot treatments. The field was prepared following the usual pre-sowing operations like disking and leveling.

Treatments: The irrigation treatments were taken as I5: five irrigations (crown root initiation (CRI), tillering, booting, flowering and milking stages), I3: three irrigations (CRI, tillering and flowering stages) and I1: one irrigation (CRI stage). The two dates of sowing treatments were taken D1: Timely sown (20^{th} Nov 2015) and D2: Late sown (9^{th} Dec 2015) during *rabi* season 2015-16 and D1: Timely sown (17^{th} Nov 2016) and D2: Late sown (7^{th} Dec 2016) during 2016-17.

Manual sowing with the help of hand held seed drill was done with the recommended spacing of 22.5 cm between rows. Utmost care was taken to keep a distance of 5cm between plants which is also followed for the wheat belt of Indo-Gangetic plains. NPK nutrients were applied as recommended dose of fertilizers i.e.120:60:60 kg ha^{-1}. Nitrogen is applied as urea fertilizer in three split doses (50% as basal during sowing, 25% during CRI stage and 25% during flowering stage). However, in case of one irrigation (I1) treatment, urea was applied at 50% as basal and 50% as top dress during CRI stage synchronizing with irrigation. 100 % P and K were applied as basal dose at the time of sowing in all treatments. The recommended cultural practices of weeding and plant protection measures were followed.

Field observation and measurements

Leaf Area Index (LAI)

Plant Canopy Analyser (LAI-2000) of LI-COR was used to measure Leaf Area Index (LAI) following the standard procedure given by Welles and Norman, 1991. Random multiple observations of LAI (at least five) were made at different points within the plot and their average was calculated to represent LAI of that plot.

Equivalent water thickness (EWT)

Equivalent leaf moisture thickness (EWT), a measure of leaf water content was computed as ratio of volume of leaf water to leaf area. The mathematical equation is as follows:

$$EWT = \frac{(w_f - w_d)}{A * \rho_w} \quad \ldots(1)$$

Where, EWT = equivalent water thickness (cm), Wf = leaf fresh weight (g), Wd= leaf dry weight (g), A = leaf area (cm^2) and ρ_w = density of water (g/cm^3).

Leaf chlorophyll content (Cab)

Fresh leaf samples from different treatments were cut and 50 mg of it was weighed accurately on an analytical balance and chlorophyll was extracted by a non-macerated method equilibrating it with 10ml DiMethylSulfOxide (DMSO) in a capped vial and keeping in an oven at 65°C for about 3hrs (Hiscox and Israelstam, 1979). The decanted solution was used to estimate the absorbance at 645 and 663nm wavelength using Spectrophotometer (Thermoscientific, Model: Evolution 300 UV Visible Spectrophotometer). The total leaf chlorophyll content was calculated using the formula given below (Arnon, 1949).

$$LCC = \frac{(20.2A_{645} + 8.02A_{663}) * V}{100 * W} \quad \ldots (2)$$

where,

LCC = total leaf chlorophyll content (mg g^{-1} of fresh weight); $A645$ = Absorbance at 645 nm; $A663$ = Absorbance at 663nm; V = final volume of chlorophyll extract in DMSO; W = weight of plant sample.

Retrieval of biophysical parameters using Spectroradiometric observation

For reflectance measurement in nadir view over wheat canopy, ASDI FieldSpec-3 hand held spectroradiometer having 25° Field of View (FOV) was used. The spectro-radiometric reflectance measurements at 1 nm interval were integrated to broadband reflectances corresponding to optical bands of Sentinel-2A MSI by using their respective band-wise relative spectral response (RSR) curves. The biophysical parameters retrieval were carried out using inversion of widely used PROSAIL-5B model (Jacquemond *et al.,* 2009) with look-up-table (LUT) approach. The model uses the input parameters in the forward mode to simulate canopy reflectance in the spectral range of 400-2500 nm at 1 nm interval (Table 1). The range of free input parameters were based on *a-priori* knowledge of

Table 1. Input parameters of PROSAIL-5B model used to generate LUT for wheat

Parameter	Abbreviation	Unit	Range of free parameters	Fixed parameters
Leaf chlorophyll content	Cab	µg cm^{-2}	20-80	
Carotenoid content	Car	µg cm^{-2}	-	1.0
Brown pigment content	Cbrown	Arbitrary units	-	0.05
Equivalent water thickness	Cw	Cm	0.01-0.04	
Dry matter content	Cm	g cm^{-2}	-	0.005
Leaf structure coefficient	N	No dimension	-	1.5
Leaf area index	LAI	m^2 m^{-2}	0.1-7.0	
Average leaf angle	Angl	Degree		
Soil coefficient	Psoil	No dimension	-	0.1
Fraction of diffuse incoming solar radiation	Skyl	No dimension		0.1
Hot-spot size parameter	Hspot	m m^{-1}		
Hot-spot flag	Ihot	No dimension	-	1 (use hot spot)
Solar zenith angle	Tts	Degree		
Sensor/view zenith angle	Tto	Degree		0
Relative azimuth	Psi	Degree		

the variation in crop biophysical parameters from the field experimental data and as reported in literature. Only three free input parameters viz., chlorophyll content (Cab), leaf area index (LAI) and equivalent water thickness (Cw) were varied. Thus, range of free input parameters and their possible combination generated large number of spectra (here 124000 cases). PROSAIL-5B simulated spectra were also integrated to reflectance corresponding to Sentinel-2 MSI, using band-wise relative spectral response (RSR) functions of respective sensors. The solution was obtained by inverting the measured broadband reflectance through minimizing the error between simulated and measured reflectance using a cost/merit function. In this study, relative mean square error (rMSE) was used as a cost function which was calculated as:

$$rMSE = \sum_{i=1}^{n} \frac{\left(R_{obs} - R_{lut}\right)^2}{R_{obs}} \qquad \ldots(3)$$

Where, R_{obs} = observed reflectance at specific spectral band *i*, R_{lut} = simulated reflectance in the LUT at that spectral band, n = number of spectral bands. To avoid ill-poised nature of inversion and increase the consistency of retrieved LAI, final solution was taken as the mean value of best 10% solutions (i.e. having smallest sorted rMSE) as reported by Sehgal *et al*. (2016).

Validation of biophysical variable retrieval

The retrieved biophysical variable was compared with in-situ measured biophysical variable and its accuracy was evaluated using coefficient of determination (R^2) and root mean square error (RMSE) and index of agreement (D-index) and ratio of performance to deviation (RPD). The RMSE was calculated using following formula:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left(BV_m - BV_r\right)^2}{N}} \qquad \ldots(4)$$

Where, BV_m = in-situ measured biophysical variable of ith field, BV_r = retrieved biophysical variable of ith field and N = number of observations.

The D-index developed by Willmott (1981) is a standardized measure of the degree of model prediction error and varies between 0 and 1. A value of 1 indicates a perfect match, and 0 indicates no agreement at all. It is calculated as:

$$D\,index = 1 - \frac{\sum_{i=1}^{n} \left(BV_r - BV_m\right)^2}{\sum_{i=1}^{m} \left(\left|BV_r - \overline{BV_m}\right| + \left|BV_m - \overline{BV_m}\right|\right)^2} \qquad \ldots(5)$$

where, $\overline{BV_m}$ = average of in-situ measured biophysical variable over all fields

Results and Discussion

Spectroradiometric reflectances were integrated to Sentinel-2 MSI sensor equivalent broadband reflectances. These broadband reflectances were used to retrieve three biophysical parameter viz., leaf chlorophyll content (Cab), equivalent water thickness (EWT) and leaf area index (LAI) of wheat under different treatments of research farm study. The biophysical variables were retrieved through inversion of PROSAIL-5B model using look-up-table approach. Because PROSAIL is one of the most accepted canopy RTM which have been inverted to derive canopy biophysical variables from hyperspectral and multispectral remote sensing observations (Darvishzadeh *et al.,* 2008; Vohland *et al.,* 2010; Sehgal *et al.,* 2016). We used LUT approach for inversion of PROSAIL because of its better performance as reported in literature (Mridha *et al.,* 2015; Chakraborty *et al.,* 2015; Sehgal *et al.,* 2016).

The comparison of observed versus retrieved Cab, EWT and LAI over different treatments in the both years using LUT inversion of MSI reflectance is shown in Figure 1-3. The results showed that retrieval of canopy chlorophyll content was largely underestimated in the season 2015-16 (Fig. 1). The observed Cab varied between 33 and 53 µg/cm^2, while retrieved Cab varied between 31 and 45 µg/cm^2 in the season 2015-16 with RMSE of 6.24 µg/cm^2. The degree of underestimation in the season 2016-17 was lower as compared to 2015-16. The RMSE of Cab retrieval was 4.97 µg/cm^2 in the season 2016-

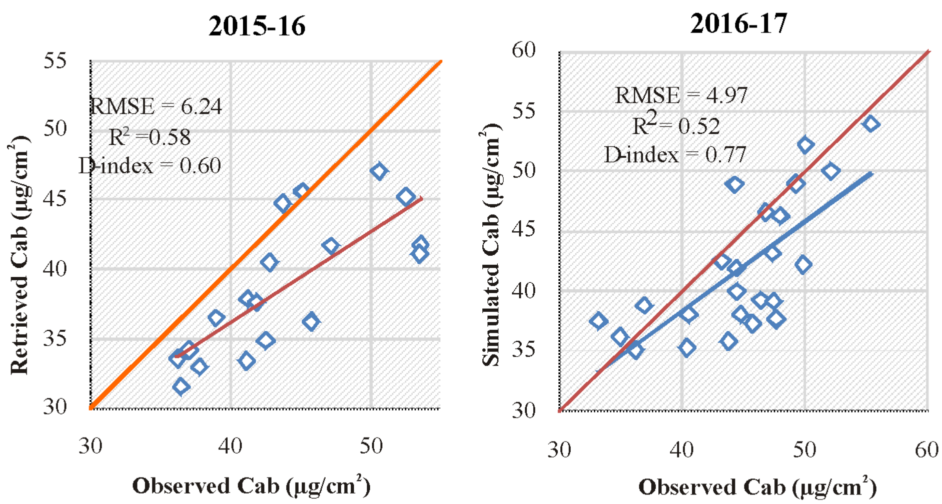

Fig. 1. Scatter plot of observed versus retrieved chlorophyll content using LUT inversion of PROSAIL model in two years (a) 2015-16 and (b) 2016-17

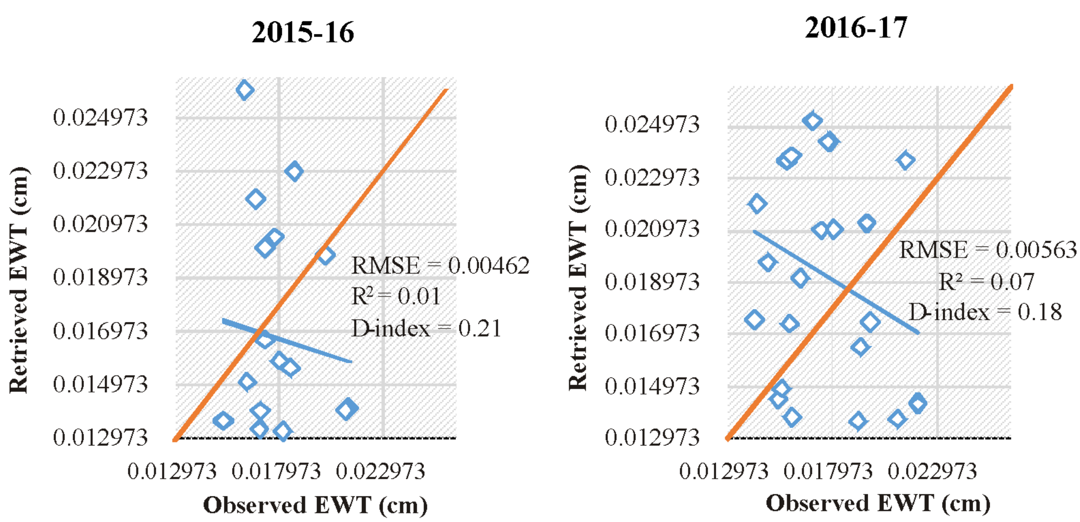

Fig. 2. Scatter plot of observed versus retrieved equivalent water thickness using LUT inversion of PROSAIL model in two years (a) 2015-16 and (b) 2016-17

17. The retrieved Cab showed poor agreement with observed Cab as shown by low R^2 of 0.58 and 0.52 in the season 2015-16 and 2016-17, respectively. This may be attributed to weak signal transmission from leaf to canopy scale resulting in relatively inaccurate retrieval of leaf biochemical variables by canopy reflectance (Asner, 1998; Jacquemoud *et al.,* 1996). Further predominant absorption in visible region by chlorophyll molecules may propagate error in PROSAIL simulations leading to relatively accurate estimation of leaf chlorophyll. Our results are in conformity with the previous studies (Mridha *et al.,* 2015; Chakraborty *et al.,* 2015; Sehgal *et al.,* 2016).

Wheat equivalent water thickness showed no agreement between measured and retrieved through model inversion as exhibited by very poor R^2 (Fig. 2). The observed EWT varied between 0.0142 cm and 0.022 cm while retrieved EWT varied between 0.0116 cm and 0.0265 cm.

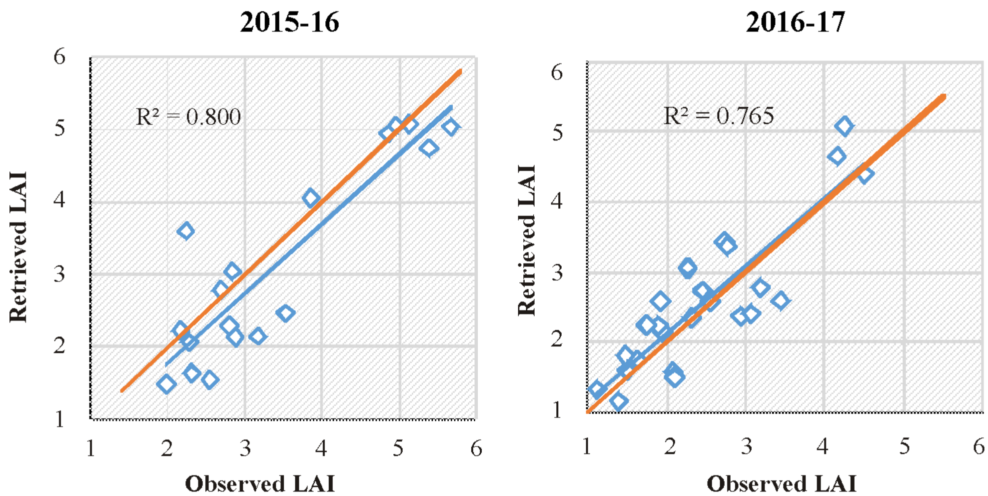

Fig. 3. Scatter plot of observed versus retrieved LAI using LUT inversion of PROSAIL model in two years (a) 2015-16 and (b) 2016-17

The normalized RMSE of EWT retrieval was 26% and 33% of observed value in 2015-16 and 2016-17, respectively. The results showed the inadequacy or failure of LUT inversion approach for EWT retrieval due to narrow range of variation in EWT (Sehgal *et al.,* 2016).

The performance of LUT based model inversion for LAI retrieval was carried out by comparison of observed and retrieved values (Fig. 3). The results showed that model inversion satisfactorily retrieved the LAI over different treatment in both the seasons. The measured LAI varied between 1.12 and 5.6 while retrieved LAI varied between 1.15 and 5.0. The retrieved LAI showed good agreement with observed one with R^2 of 0.77 and 0.80, RMSE of 0.64 and 0.49 and D-index of 0.93 and 0.92 in the season 2015-16 and 2016-17, respectively.

Overall the accuracy of biophysical parameters retrieval through inversion of PROSAIL model using LUT approach from Sentinel-2 MSI sensor followed the order of LAI > Cab > EWT. As LAI is one of the aspect to determine canopy architecture, relatively accurate retrieval of LAI may be ascribed to fact that canopy architecture significantly contribute to total canopy reflectance than biochemical parameters (Kneubuhler, 2002; Vohland and Jarmer, 2008). Moreover, changes in LAI has large influence on reflectances in NIR and Red wavelength regions and has moderate sensitivity in Green wavelength region may also contribute to better simulation by PROSAIL resulted in relatively accurate inversion (Jacquemoud *et al.,* 2009).

Conclusions

A field experiment with different treatments of date of sowing and water stress was conducted to create the variation in leaf chlorophyll content (Cab), leaf area index (LAI) and leaf moisture content (EWT) in wheat. The spectroradiometric observations in different treatments were converted to equivalent Sentinel-2 satellite multispectral bands. The study focuses on simultaneous retrieval of leaf chlorophyll content (Cab), leaf area index (LAI) and leaf moisture content (EWT) in wheat through look-up-table inversion of PROSAIL canopy radiative transfer model from equivalent Sentinel-2 multispectral data. The accuracy of biophysical parameters retrieval through inversion of PROSAIL model using LUT approach sensor followed the order of LAI > Cab > EWT. Thus, the PROSAIL model can be used successfully for retrieval of LAI, but require its further improvements for retrieval of Cab and EWT.

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