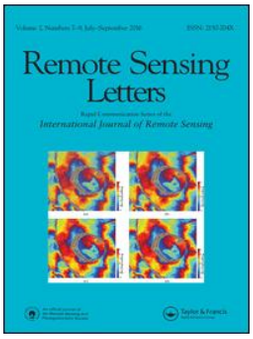

Remote Sensing Letters

ISSN: 2150-704X (Print) 2150-7058 (Online) Journal homepage: http://www.tandfonline.com/loi/trsl20

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To cite this article: Anatoly A. Gitelson (2019) Remote estimation of fraction of radiation absorbed by photosynthetically active vegetation: generic algorithm for maize and soybean, Remote Sensing Letters, 10:3, 283-291, DOI: 10.1080/2150704X.2018.1547445

To link to this article: https://doi.org/10.1080/2150704X.2018.1547445

Published online: 27 Nov 2018.

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REMOTE SENSING LETTERS
2019, VOL. 10, NO. 3, 283–291
https://doi.org/10.1080/2150704X.2018.1547445

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Remote estimation of fraction of radiation absorbed by photosynthetically active vegetation: generic algorithm for maize and soybean

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ABSTRACT
The objective of this study is to develop generic algorithm for estimating fraction of radiation absorbed by photosynthetically active vegetation not requiring parameterization for C3 and C4 crops, maize and soybean, with contrasting photosynthetic pathways, canopy architectures and leaf structures. The study based on data acquired during eight years, altogether 16 site years of maize (12 irrigated and 4 rainfed, nine hybrids) and for 8 site years of soybean (4 irrigated and 4 rainfed, three cultivars). The red edge normalized difference vegetation index (NDVI), green NDVI and wide dynamic range vegetation index (WDRVI) were found to be accurate in estimating fraction of photosynthetically active radiation (PAR) absorbed by photosynthetically active green vegetation in maize and soybean with root mean squared error (RMSE) of 0.057, 0.067 and 0.069, respectively.

ARTICLE HISTORY
Received 31 July 2018
Accepted 30 October 2018

1. Introduction

Terrestrial vegetation constitutes a major element of the interface between the land surface and the atmosphere. Quantifying the biophysical traits of vegetation and their temporal variation is important for assessment of the vegetation status and its response to changing environmental conditions. Fraction of absorbed photosynthetically active radiation (fAPAR) is one of the main trait used in the production efficiency models (PEM). Numerous studies (e.g., Asrar et al. 1992; Sellers 1985) found that fAPAR can be estimated remotely using the Normalized Difference Vegetation Index, NDVI (Rouse et al. 1974). Several PEMs used NDVI to estimate primary production (e.g., Running et al. 2004). However, linear relationship between fAPAR and NDVI is only valid during the growing stage (Ruimy, Saugier, and Dedieu 1994; Sims et al. 2006; Gitelson, Peng, and Huemmrich 2014). In addition, a significant decrease in the sensitivity of NDVI has been observed for fAPAR exceeding 0.7 (e.g., Asrar et al. 1984), masking changes in vegetation with moderate-to-high biomass. Since only the green photosynthetic components of the canopy are used for photosynthesis, fAPAR has to be separated into photosynthetically active green

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component ($fAPAR_{green}$) and non-photosynthetically active components (e.g., Hall et al. 1992, Vina and Gitelson, 2005; Bacour et al. 2006; Zhang et al. 2014).

The precision of $fAPAR_{green}$ estimation is especially important now as solar-induced chlorophyll fluorescence (SIF) has been demonstrated to be an efficient tool for monitoring primary productivity, (e.g., Porcar-Castell et al. 2014; Liu et al. 2018). However, SIF may be used as an accurate measure of gross primary production (GPP), if one has accurate knowledge and correction of SIF escape probability and accurate measurement of $fAPAR_{green}$ is crucial for that. Thus, as Liu et al. (2018) underlined 'absorbed PAR is a bridge linking SIF to GPP'.

fAPAR was estimated using inversion of radiative transfer models, derivatives of reflectance spectra, neural networks, and multi-spectral statistical approaches. The most common approach is the use of vegetation indices (VI), combination of visible and near-infrared reflectance. However, it does not clear whether VIs are able to accurately estimating $fAPAR_{green}$ in cultivars the same species or in other species with no algorithm re-parameterization. Thus, testing the ability of VIs to estimate fAPAR requires multiyear studies involving different species with different cultivars and hybrids growing in widely variable weather conditions. We took advantage of the Carbon Sequestration Program at University of Nebraska-Lincoln (UNL), which presented a unique possibility for measuring multiyear $fAPAR_{green}$ at closely located irrigated and rainfed maize and soybean sites. The data sets allowed us to answer a pivotal question: whether is it possible to estimate $fAPAR_{green}$ accurately in different hybrids and cultivars of two contrasting C3 and C4 crops, maize and soybean, having different photosynthetic pathways, leaf structures and canopy architectures? We developed the relationships $fAPAR_{green}$/VIs for 16 site years of maize data (12 irrigated and 4 rainfed) and for 8 site years of soybean data (4 irrigated and 4 rainfed). Nine maize hybrids and three soybean cultivars were grown during the eight years. These data allowed to assess accuracy of $fAPAR_{green}$ estimation in crops under the rather harsh weather conditions of eastern Nebraska including years with very different temperature regimes and water supplies.

The objective of this study is to evaluate different vegetation indices for the remote estimation of the fraction of radiation absorbed by photosynthetically active vegetation in C3 and C4 crops and to devise generic algorithms for maize and soybean not requiring parameterization for these crops.

2. Methods

Three AmeriFlux sites (Mead Irrigated/US – Ne1, Mead Irrigated Rotation/US – Ne2, and Mead Rainfed Rotation/US – Ne3), located at UNL Eastern Nebraska Research and Extension Center, Nebraska, USA, were studied during growing seasons from 2001 to 2008 as part of the Carbon Sequestration Project at UNL (http://ameriflux.lbl.gov/). It consisted of three agricultural sites; the first two are fields with center pivot irrigation systems; the third site is the same size, but relies entirely on rainfall. Site 1 is under continuous maize, sites 2 and 3 are under maize-soybean rotation (Suyker et al. 2005).

Within each of three study sites were six small plot areas representing all major occurrences of soil and crop production zones (Suyker et al. 2005). For each plot, leaf area index (LAI) was estimated from destructive samples taken during the growing season at 10–14 day intervals. On each sampling date, plants from a one meter length

of each of two rows within each plot were collected and the total number of plants recorded. Plants were kept on ice and transported to the laboratory where they were separated into green leaves, senesced (yellow or brown) leaves, stems, and reproductive components. Green and senesced leaves were run through an area meter (LI-3100, Li-Cor, Inc., Lincoln, Nebraska, USA) and the total leaf area per plant was determined. For each plot, the total leaf area per plant was multiplied by the plant population to obtain a total leaf area index (LAI_{total}). LAI_{total} for the six plots were then averaged as a site-level value (additional details in Vina et al., 2011). Green leaves were handled in the same way to obtain the green LAI (LAI_{green}).

Hourly measurements of photosynthetically active radiation (PAR) were obtained using the following procedures: incoming PAR (PAR_{inc}) was measured with Li-Cor (Lincoln, NE) point quantum sensors pointing to the sky, and placed at 6 m from the ground. PAR reflected by the canopy and soil (PAR_{out}) was measured with Li-Cor point quantum sensors pointing down, and placed at 6 m above the ground. PAR transmitted through the canopy (PAR_{transm}) was measured with Li-Cor line quantum sensors placed at about 2 cm above the ground, looking upward; PAR reflected by the soil (PAR_{soil}) was measured with Li-Cor line quantum sensors placed about 12 cm above the ground, looking downward (details by Hanan et al. 2002). Daytime PAR values were calculated by integrating the hourly measurements during a day from sunrise to sunset (period when PAR_{inc} exceeded 1 μmol m^{-2} s^{-1}). Daytime PAR_{inc} values are reported in MJ m^{-2} day^{-1} (Suyker et al. 2005).

Absorbed PAR (APAR) was calculated as Goward and Huemmerich (1992):

$$APAR = PAR_{inc} - PAR_{out} - PAR_{transm} + PAR_{soil} \tag{1}$$

fAPAR and $fAPAR_{green}$ (Hall et al. 1992) were calculated as:

$$fAPAR = APAR/PAR_{inc} \tag{2}$$

$$fAPAR_{green} = fAPAR \times \left(LAI_{green}/LAI_{total}\right) \tag{3}$$

Spectral reflectance measurements at the canopy level were made using hyperspectral radiometers mounted on an all-terrain sensor platform (Rundquist et al. 2014). A dual-fiber optic system, with two Ocean Optics USB2000 radiometers in the range of 400–1100 nm with a spectral resolution of about 1.5 nm, was used to collect radiometric data. One radiometer equipped with a 25° field-of-view optical fiber was pointed downward to measure the upwelling radiance of the crop; the height of this radiometer was kept constant above the top of canopy (5.4 m) throughout the growing season yielding a sample area with a diameter of 2.4 m. The other radiometer was pointed upward to simultaneously measure the incident irradiance. Radiometric data was collected close to solar noon (between 11:00 and 13:00 local time), when changes in solar zenith angle were minimal; percent reflectance was then computed based on those measured radiance and irradiance (details are in Gitelson et al., 2006 and Viña et al. 2011). For each site, six randomly selected plots were established with six randomly selected sampling points. A total of 36 spectra per site were sampled at each data acquisition, and their median was used as the site reflectance.

In this study, we tested thirteen VIs that previously were evaluated as the best for fAPAR estimation. The collected reflectance spectra were resampled to spectral bands of

Moderate Resolution Imaging Spectroradiometer – MODIS (green: 545–565 nm, red: 620–670 nm, and NIR: 841–876 nm) using MODIS spectral response function and simple ratio (SR), NDVI, enhance vegetation index 2 (EVI2), modified triangular vegetation index (MTVI1 and MTVI2), green visible atmospherically resistant index ($VARI_{green}$), optimized soil-adjusted vegetation index (OSAVI), $WDRVI_{\alpha = 0.5}$, and Green NDVI were calculated. The reflectance spectra were also resampled to spectral bands of the Multi Spectral Instrument (MSI) on the Sentinel-2 satellite system (green: 550–580 nm, red: 660–670 nm, red edge 1: 693–712 nm, red edge 2: 732–748 nm and NIR: 773–793 nm) using MSI spectral response function and medium resolution imaging spectrometer (MERIS) terrestrial chlorophyll index (MTCI), $VARI_{red\ edge}$, and red edge NDVI were calculated.

3. Results and discussion

In both crops, maize and soybean, fAPAR shows a progressive increase during the vegetative stage until maximum canopy development, remains virtually invariant during the reproductive stage, with a decrease during the senescence stage (Figure 1). The $fAPAR_{green}$ is a measure of the fAPAR absorbed only by the photosynthetic component of the vegetation (Goward and Huemmerich 1992; Hall et al. 1992). In reproductive and senescence stages, the behavior of $fAPAR_{green}$ is very different from that of fAPAR; it decreases significantly during reproductive stage and drops drastically in senescence. During these stages, both photosynthetic and non-photosynthetic components of the crops absorb PAR, but the contribution of the photosynthetic component decreases considerably toward the end of the growing season. While the canopy is still intercepting PAR, it is progressively used less for photosynthesis.

The relationship between NDVI and $fAPAR_{green}$ was almost non-species-specific (Figure 2). Thus, NDVI supposed to be a proxy of $fAPAR_{green}$; however, NDVI/$fAPAR_{green}$ relationship is asymptotic with a decrease in the slope as $fAPAR_{green}$ exceeds 0.7 (see first derivative dNDVI/$dfAPAR_{green}$ in Figure 2). This has been also reported by several authors (e.g., Baret and Guyot, 1991; Myneni, Nemani, and Running 1997). Thus, NDVI exhibits limitations at moderate-to-high vegetation density.

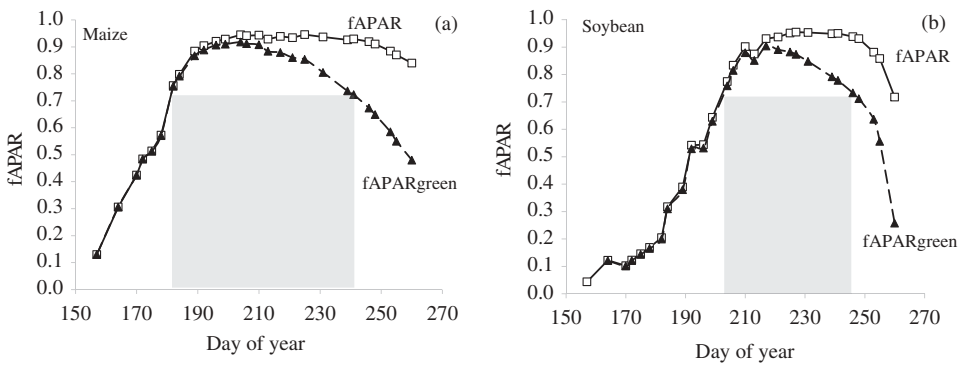

Figure 1. fAPAR and $fAPAR_{green}$ in maize (A) and soybean (B) plotted against day of year. Changes in $fAPAR_{green}$ (shaded areas) correspond to time in the season when $fAPAR_{green} > 0.7$ and sensitivity of NDVI to $fAPAR_{green}$ drops drastically (see first derivative dNDVI/$dfAPAR_{green}$ in Figure 2).

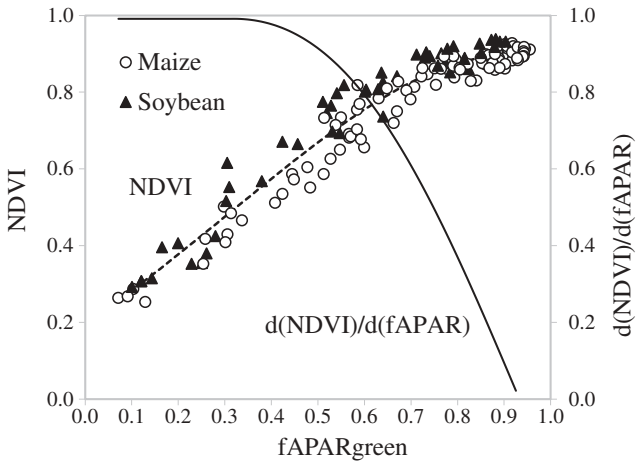

Figure 2. NDVI calculated with reflectance in spectral bands of MODIS and first derivative of NDVI with respect to $fAPAR_{green}$ (solid line) plotted against $fAPAR_{green}$ in maize and soybean. Dash line is best fit function for NDVI vs. $fAPAR_{green}$ relationship.

As $fAPAR_{green}$ exceeds 0.7, root mean square error (RMSE) of $fAPAR_{green}$ estimation by NDVI grows exponentially, reaching 0.25 for $fAPAR_{green}$ = 0.8. It means that in crop studied for more than two months during growing season NDVI does not bring reliable information about $fAPAR_{green}$ (Figure 1).

EVI and EVI2 were developed to increase the sensitivity of NDVI to moderate to high vegetation density and were shown to be effective estimating LAI (Huete et al. 1997; Jiang et al. 2008]. They also were widely used as a measure of $fAPAR_{green}$ (e.g., Xiao et al. 2004). EVI and EVI2 were closely related to $fAPAR_{green}$ < 0.7 but further increase of EVI from 0.6 to 0.9 did not relate to $fAPAR_{green}$ (Figure 3). For crop studied, slope of $fAPAR_{green}$/LAI relationship increased gradually until LAI reached 3–4 and then it dropped due to decrease in depth of light penetration inside the canopy and decrease of chlorophyll efficiency in light absorption (Peng et al. 2011; Gitelson et al. 2016). Thus,

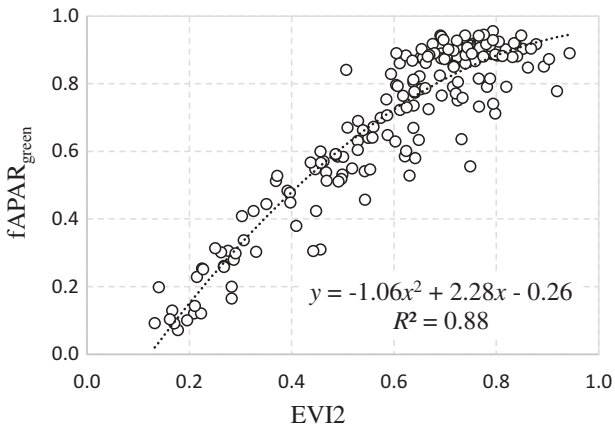

Figure 3. Relationship between $fAPAR_{green}$ and EVI2 for maize and soybean.

for LAI > 3, EVI2 did follow increase in LAI (Figure 3 in Viña et al. 2011) while $fAPAR_{green}$ increased a little that disturbs close $fAPAR_{green}$/EVI relationship.

Among VIs tested only three of them had close linear not species specific relationships with $fAPAR_{green}$ – $WDRVI_{\alpha = 0.5}$ (Gitelson 2004), green NDVI (Gitelson, Kaufman, and Merzlyak 1996), and red edge NDVI (Gitelson and Merzlyak 1994). All three VIs were developed to avoid NDVI limitation of estimating biophysical characteristics of dense vegetation. Main reasons for decrease of NDVI sensitivity to high density vegetation are (i) high ρ_{NIR}/ρ_{red} ratio that reaches 7–10 for moderate to high density vegetation, and (ii) saturation of red reflectance. $WDRVI = (\alpha\rho_{NIR} - \rho_{red})/(\alpha\rho_{NIR} + \rho_{red})$ is modification of NDVI attenuating the effect of near infra-red (NIR) reflectance by $\alpha < 1$. It makes magnitudes of $\alpha\rho_{NIR}$ and ρ_{red} comparable and increases the sensitivity of WDRVI to such traits of dense vegetation as vegetation fraction and LAI (Gitelson 2004). The $fAPAR_{green}/WDRVI_{\alpha = 0.5}$ relationship was not species specific with $R^2 = 0.92$ ($p < 0.001$) and RMSE = 0.069 (Figure 4a, Table 1). Close relationship between $WDRVI_{\alpha = 0.5}$ and $fAPAR_{green}$ simulated by SCOPE (soil canopy observation, photochemistry and energy fluxes) radiative transfer model with LAI varied from 1 to 4, leaf chlorophyll content (20–80 μg cm^{-2}), solar zenith angle 20–60° and three typical leaf inclination distribution functions (planophile, plagiophile and spherical) was found by Liu et al. (2018).

The use of green and red edge spectral bands instead of red in NDVI is another way to increase the sensitivity of NDVI-like vegetation indices to traits of high density vegetation (Buschmann and Nagel 1993; Gitelson and Merzlyak 1994; Gitelson, Kaufman, and Merzlyak 1996). In spectral regions located far from main red absorption band of chlorophyll (in situ around 670 nm), absorption coefficient of chlorophyll is not higher than 1–2% of the red (Lichtenthaler 1987) and pathway of light inside the canopy is much larger than in red (Merzlyak and Gitelson 1995). So, with increase in vegetation density absorbance continue to increase enhancing sensitivity of the green and red edge reflectance to $fAPAR_{green}$.

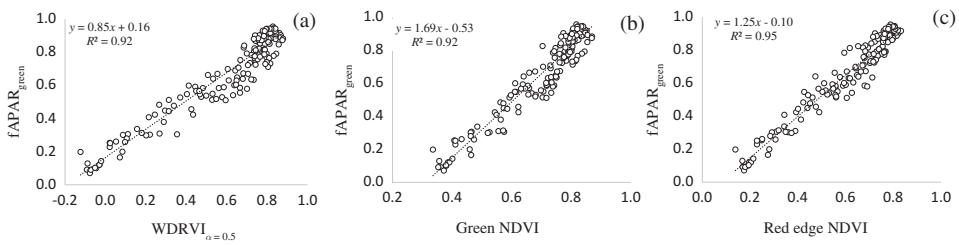

Figure 4. $fAPAR_{green}$ plotted against (a) $WDRVI_{\alpha = 0.5}$, (b) green NDVI and (c) red edge NDVI for maize and soybean.

Table 1. Algorithms, determination coefficients, and RMSE of $fAPAR_{green}$ estimation in maize and soybean by vegetation indices.

VI	$fAPAR_{green}$ vs. VI	R^2	RMSE
EVI2	$y = -1.06x^2 + 2.28x - 0.26$	0.88	0.096
NDVI	$y = 0.07e^{2.81x}$	0.92	0.075
$WDRVI_{\alpha = 0.5}$	$y = 0.85x + 0.16$	0.92	0.069
Green NDVI	$y = 1.6891x - 0.5271$	0.92	0.067
Red edge NDVI	$y = 1.2531x - 0.1035$	0.95	0.057

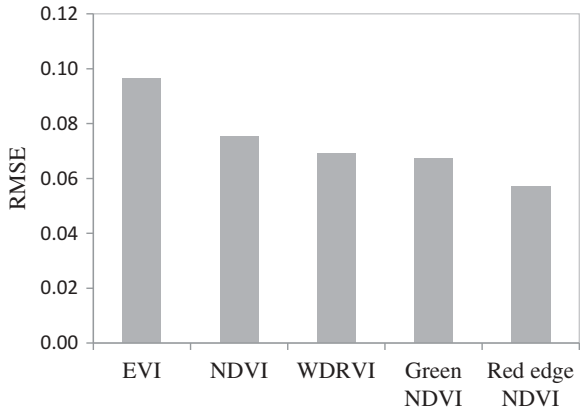

Figure 5. Root mean square error of $fAPAR_{green}$ estimation using different vegetation indices.

The relationships of $fAPAR_{green}$ vs. green NDVI and $fAPAR_{green}$ vs. red edge NDVI were found to be very close ($p < 0.001$) with $R^2 = 0.92$ and 0.95, respectively (Figure 4, Table 1). Red edge NDVI appears to be the best index for $fAPAR_{green}$ estimation in the whole range of its variation (Figure 5). The algorithms presented in Table 1 are not species specific for maize and soybean and do not require parameterization for these crops.

4. Conclusions

Performance of 13 vegetation indices in estimating fraction of radiation absorbed by photosynthetically active vegetation $fAPAR_{green}$ in C3 and C4 crops was studied. Three of them, $WDRVI_{\alpha = 0.5}$, green NDVI and red edge NDVI, have close linear relationship with $fAPAR_{green}$ not requiring parameterization for crops contrasting in leaf structures, canopy architectures and photosynthetic pathways. All three indices exhibited a strong sensitivity to $fAPAR_{green}$ across two contrasting species, their hybrids and cultivars and may be used as an accurate proxy of $fAPAR_{green}$. The implications of these findings are far-reaching since the described techniques open a new possibility for an accurate estimation of crop biophysical characteristics at different scales.

The choice of the index depends on the spectral characteristics of the radiometer or the satellite sensor being used. The indices employing red edge spectral bands can be used for retrieving $fAPAR_{green}$ from Sentinel 2 and Sentinel 3 satellite data. The indices employing green spectral band can be used for $fAPAR_{green}$ estimating by Landsat and MODIS with 500 m and 1 km spatial resolution. The NDVI and $WDRVI_{\alpha = 0.5}$ with the red and NIR bands can be used for crop monitoring by such satellite systems as Landsat, Sentinel 2 and 3, MODIS (250 m resolution) and AVHRR.

Acknowledgments

The support and the use of facilities and equipment provided by the Center for Advanced Land Management Information Technologies (CALMIT) the School of Natural Resources and the Carbon Sequestration Program at the University of Nebraska-Lincoln is greatly appreciated.

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