An Evaluation of MODIS 250-m Data for Green LAI Estimation in Crops

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[1] Green leaf area index (LAI) is an important variable for climate modeling, estimates of primary production, agricultural yield forecasting, and many other diverse applications. Remotely sensed data provide considerable potential for estimating LAI at local, regional, and global scales. The goal of this study was to retrieve green LAI from MODIS 250-m vegetation index (VI) data for irrigated and rainfed maize and soybeans. The performance of both MODIS-derived NDVI and Wide Dynamic Range Vegetation Index (WDRVI) were evaluated across three growing seasons (2002 through 2004) over a wide range of LAI and also compared to the performance of NDVI and WDRVI derived from reflectance data collected at close-range across the same field locations. The NDVI vs. LAI relationship showed asymptotic behavior with a sharp decrease in the sensitivity of the NDVI to LAI exceeding 2 m^2/m^2 for both crops. WDRVI vs. LAI relation was linear across the entire range of LAI variation with determination coefficients above 0.93. Importantly, the coefficients of the close-range WDRVI vs. LAI equation and the MODIS-retrieved WDRVI vs. LAI equation were very close. The WDRVI was found to be capable of accurately estimating LAI across a much greater LAI range than the NDVI and can be used for assessing even slight variations in LAI, which are indicative of the early stages of plant stress. These results demonstrate the new possibilities for analyzing the spatio-temporal variation of the LAI of crops using multi-temporal MODIS 250-m imagery.
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1. Introduction

[2] One of the key variables required for estimating primary production and global climate studies is leaf area index (LAI). Remote estimations of LAI at regional to global scales can be performed using transforms of spectral reflectance, called vegetation indices (VIs) [e.g., *Rouse et al.*, 1974]. A physically-based algorithm for estimating LAI from NDVI observations has been developed [e.g., *Myneni et al.*, 1997]. However, the relationship between NDVI and LAI is essentially non-linear and suffers a rapid decrease of sensitivity at moderate-to-high densities of photosynthetic green biomass [*Asrar et al.*, 1984; *Goward and Huemmerich*, 1992; *Myneni et al.*, 1997; *Gitelson et al.*, 2003; *Gitelson*, 2004].

[3] Alternative methods have been proposed that yield more linear relationships between remotely sensed data and percent canopy cover, LAI, and green biomass [e.g., *Chen and Cihlar*, 1996; *Gao et al.*, 2000; *Gitelson et al.*, 2003]. However, these methods require spectral channels that are not available at the 250-m spatial resolution of the Moderate Resolution Imaging Spectroradiometer (MODIS). The Wide Dynamic Range Vegetation Index (WDRVI) was recently proposed to improve NDVI sensitivity under moderate to high densities of green biomass [*Gitelson*, 2004] and only requires spectral information from the red and near-infrared (NIR) regions, which are represented in MODIS' two 250-m spectral bands. The WDRVI's effectiveness has been demonstrated at the field-level with close-range sensing over crops [*Gitelson*, 2004]. It has also proven effective for monitoring vegetation dynamics in the US with Advanced Very High Resolution Radiometer 1-km data [*Viña et al.*, 2004], and tropical forests with 30-m Landsat Thematic Mapper data [*Aguilar-Amuchastegui and Henebry*, 2006]. WDRVI takes the following form:

$$\mathrm{WDRVI} = (\alpha \times \rho_{\mathrm{NIR}} - \rho_{\mathrm{red}})/(\alpha \times \rho_{\mathrm{NIR}} + \rho_{\mathrm{red}}) \quad (1)$$

where α is a weighting coefficient and ρ_{NIR} and ρ_{red} are reflectances in the NIR and the red bands, respectively. When $\alpha = 1$, the equation yields the conventional NDVI formulation [*Rouse et al.*, 1974]. With $\alpha < 1$, the contribution from the NIR band is attenuated, making it comparable in magnitude to the red band values. This is particularly important under conditions of moderate to high green biomass, when $\rho_{\mathrm{NIR}} \gg \rho_{\mathrm{red}}$ [e.g., *Gitelson*, 2004]. The specific magnitude of α depends on sensor characteristics and atmospheric conditions. Values between 0.1 and 0.2 have been found to be effective for proximal sensing of LAI and vegetation fraction in row crops [*Gitelson*, 2004] and also for satellite observations [*Viña et al.*, 2004; *Aguilar-Amuchastegui and Henebry*, 2006].

[4] The MODIS instrument holds considerable potential for advancing our capabilities to estimate and monitor the biophysical characteristics of vegetation across large geographic areas. MODIS provides a near-daily global coverage of moderate resolution (250-m) data in the red and NIR spectral regions that are well calibrated, atmospherically corrected, and have relatively high geolocational accuracy [*Wolfe et al.*, 2002]. The value of MODIS 250-m surface reflectance and VI data for various agricultural-related land use/land cover characterization activities such as crop type mapping [*Wardlow and Egbert*, 2007; *Wardlow et al.*, 2007], crop rotation mapping [*Brown et al.*, 2007; *Morton et al.*, 2006], phenological monitoring [*Wardlow et al.*, 2006], and sub-pixel fractional estimation of crop area

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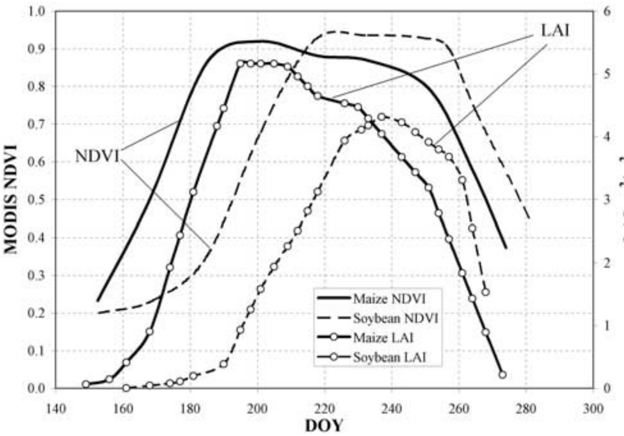

Figure 1. Temporal behavior of MODIS-derived NDVI and green leaf area index in maize and soybean.

[*Lobell and Asner*, 2004] has been well demonstrated. However, the utility of MODIS 250-m data for quantitatively estimating biophysical characteristics of crops has not been investigated to date.

[5] In this paper, the performance of NDVI and WDRVI for estimating green LAI of crops with different canopy architecture and leaf structure (maize and soybeans) using MODIS 250-m data was tested. The MODIS-derived results were also compared with performance of these indices retrieved from reflectance data collected at close-range across the same field locations.

2. Data and Methods

[6] This study used three sites located at the University of Nebraska-Lincoln's Agricultural Research and Development Center near Mead, Nebraska, USA. These sites are large cropped fields ranging in size from 49 to 65 ha. Two sites (site 1: 41°09′54.2″N, 96°28′35.9″W; site 2: 41°09′53.5″N, 96°28′12.3″W) are irrigated, while the third site (site 3: 41°10′46.8″N, 96°26′22.7″W) is not irrigated. The study was conducted using data obtained during three growing seasons (2002–2004). In 2002 and 2004, one field (site 1) was planted to maize (*Zea mays*) and two fields (sites 2 and site 3) to soybeans (*Glycine max*). In 2003, all three fields were planted to maize. Within each field, six plot areas (20-m by 20-m) called intensive measurement zones (IMZs) were established for detailed process-level studies including LAI measurements. All major occurrences of soil and crop production zones within each field were represented in this set of six IMZs. For each sampling date, destructive LAI measurements were carried out and the LAI of the IMZs were then averaged to obtain a field-level LAI value (details given by *Gitelson et al.* [2003]).

[7] Spectral measurements were made at six plots per field with each plot having six randomly selected sampling points. A dual-fiber system, with two inter-calibrated Ocean Optics USB2000 radiometers were positioned ~6-m above the top of canopy [*Gitelson et al.*, 2003]. The data were collected across a wavelength range from 400 to 900 nm with a spectral resolution of ~1.5 nm. The measurements were carried out approximately once every 5 days from the beginning of May to the beginning of October. A total of 31 data collection campaigns were conducted in both 2002 and 2004 and 34 campaigns in 2003.

[8] NDVI was calculated from the hyperspectral data as $(\rho_{NIR} - \rho_{red})/(\rho_{NIR} + \rho_{red})$ where $\rho_{NIR} = \rho_{840-880}$ and $\rho_{red} = \rho_{630-690}$ are simulated reflectance values corresponding to NIR and red spectral bands of MODIS, respectively. WDRVI was calculated using equation (1) with $\alpha = 0.2$ and the reflectance data simulated for the MODIS red and NIR bands. With $\alpha = 0.2$, the product $\alpha \times \rho_{NIR}$ becomes comparable in magnitude to ρ_{red} (5–10%) and thus, WDRVI is sensitive to change in moderate to high LAI.

[9] A time series of 16-day composite MODIS 250-m NDVI data (MOD13Q1 V004) spanning from May through October (10 composite periods) for each study year were acquired over the three sites. The NDVI data for MODIS tile h10v04 were extracted for each composite period, reprojected to the Lambert Azimuthal Equal Area projection, and sequentially stacked to create the 10-date NDVI time series for each year. Each field was then geolocated on the MODIS imagery and the time-series NDVI data were extracted for a 3-by-3 pixel window that was centered near the middle of the field. Given the fields' large size and MODIS' 250-m spatial resolution, a block of nine pixels located completely within each field's boundaries could be selected. The median NDVI value of the fields' nine pixels was then calculated for each composite period to produce the time series of MODIS NDVI data for the three growing seasons analyzed in this study. A comparable time series of WDRVI values were also calculated from the median NDVI data sets using following equation [*Viña and Gitelson*, 2005] with $\alpha = 0.2$:

$$\mathrm{WDRVI} = [(\alpha + 1)\mathrm{NDVI} + (\alpha - 1)]/[(\alpha - 1)\mathrm{NDVI} + (\alpha + 1)] \quad (2)$$

[10] To compare the sensitivity of each VI to changes in LAI, a noise equivalent LAI (NE ΔLUE) was calculated as:

$$\mathrm{NE}\ \Delta\mathrm{LAI} = \mathrm{RMSE}(\mathrm{VI\ vs.\ LAI})/[d(\mathrm{VI})/d(\mathrm{LAI})] \quad (3)$$

Where RMSE (VI vs. LAI) is the root mean squared error of the relationship VI vs. LAI and d(VI)/d(LAI) is first derivative of VI with respect to LAI. The noise equivalent metric allows for direct comparisons among different indices with different scales and dynamic ranges [*Viña and Gitelson*, 2005].

3. Results and Discussion

[11] This series of MODIS images provided observations for all physiological stages (green-up, reproduction and senescence) of maize and soybeans. The LAI varied widely across the growing season for the three fields, reaching a maximum of 6 m^2/m^2 in maize and 5.1 m^2/m^2 in soybeans. Thus, the remote sensing technique used for LAI estimation must have a wide dynamic range across the highly variable crop conditions encountered across the growing season.

[12] During the early growing season, the NDVI increase tracked well with the increase in maize LAI until the LAI exceeded 2 m^2/m^2 (Figure 1). Then, the LAI continued to increase substantially, while the NDVI only slightly increased ranging from 0.86 and 0.92 between day of year

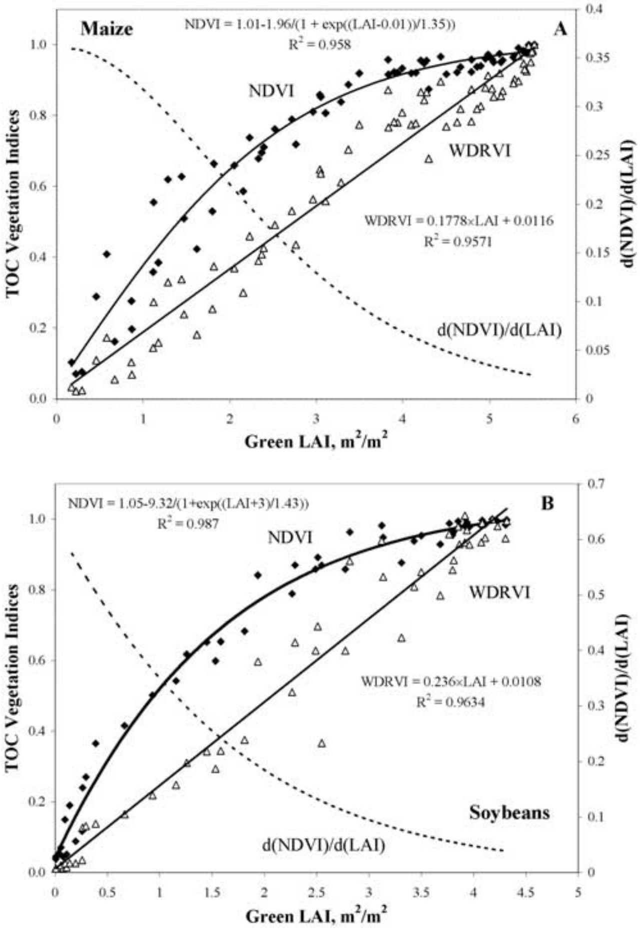

Figure 2. Scaled, $(VI - VI_{min})/(VI_{max} - VI_{min})$, NDVI and WDRVI retrieved from reflectance measured 6 meters above the top of crop canopy plotted versus leaf area index in irrigated and rainfed (a) maize and (b) soybean. Solid lines are best fit functions for VI vs. green LAI relations; dashed lines are first derivatives of NDVI with respect to LAI, d(NDVI)/d(LAI).

(DOY) 185 to 245. For soybeans, NDVI became almost invariable between DOY 210 and 255, while the LAI changed considerably.

[13] The relationship between the top of canopy (TOC) NDVI acquired at close range and LAI was essentially non-linear for both crops (Figure 2). The slope of NDVI vs. LAI relation for maize (d(NDVI)/d(LAI) in Figure 2a) decreased 2-fold for LAI = 2.5 m^2/m^2 and 9-fold for LAI = 5 m^2/m^2. NDVI exhibited the same behavior for soybeans; the sensitivity of NDVI to LAI decreased 3-fold at LAI = 2 m^2/m^2 and 11-fold for LAI = 5 m^2/m^2 (Figure 2b). This prevents an accurate estimation of LAI > 2 m^2/m^2, which occurs for more than two months of the growing season for maize and 1.5 months for soybeans. Relationships between TOC WDRVI and LAI for both crops were linear with a determination coefficient (R^2) > 0.95 for maize (Figure 2a) and > 0.96 for soybeans (Figure 2b).

[14] Relationships between MODIS-retrieved VIs and LAI were very similar to that taken at close range (Figure 3): NDVI had a non-linear asymptotic relationship and WDRVI had a linear relationship. MODIS WDRVI accounted for more than 93% of LAI variation in both crops. The RMSE of the LAI estimation was 0.49 m^2/m^2 in maize and 0.41 m^2/m^2 in soybeans. Importantly to note, the coefficients of the close-range TOC WDRVI vs. LAI equation and the MODIS-retrieved WDRVI vs. LAI equation were very close (see equations in Figures 2 and 3). This indicates that the MODIS data had high quality atmospheric correction, which produced comparable VI values to those acquired by radiometers at close range to the crop canopy.

[15] The noise equivalent of LAI (NE ΔLAI) by WDRVI was invariable with LAI and equaled 0.46 m^2/m^2 for maize and 0.34 m^2/m^2 for soybeans. The ratios of noise equivalents of LAI estimation by MODIS-retrieved NDVI (NE ΔLAI_{NDVI}) to that of WDRVI (NE ΔLAI_{WDRVI}) for both crops are shown in Figure 4. When the ratio was <1, NDVI was a more accurate index; when the ratio was >1, WDRVI was more accurate in LAI retrieval. Thus, the ratio provides a quantitative measure of the efficiency of LAI estimation. The ratio was between 0.75 and 1 for LAI < 1.4 m^2/m^2 in soybeans and < 1.5 m^2/m^2 in maize. However, for LAI > 2 m^2/m^2 the ratio increased exponentially for both crops. Thus, for LAI > 1.5 m^2/m^2, the WDRVI was more accurate than the NDVI for the LAI estimation using

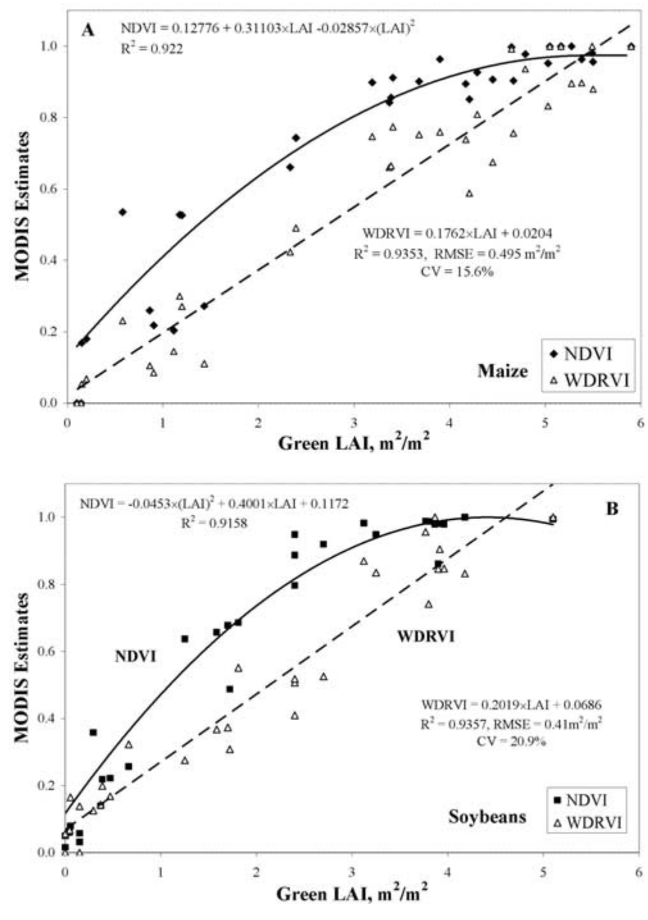

Figure 3. Scaled, $(VI - VI_{min})/(VI_{max} - VI_{min})$, NDVI and WDRVI retrieved from MODIS 250-m imagery in (2002 through 2004) plotted versus leaf area index in irrigated and rainfed (a) maize and (b) soybeans. Solid lines are best fit functions for NDVI vs. LAI relations; dashed lines are best fit functions for WDRVI vs. LAI relations.

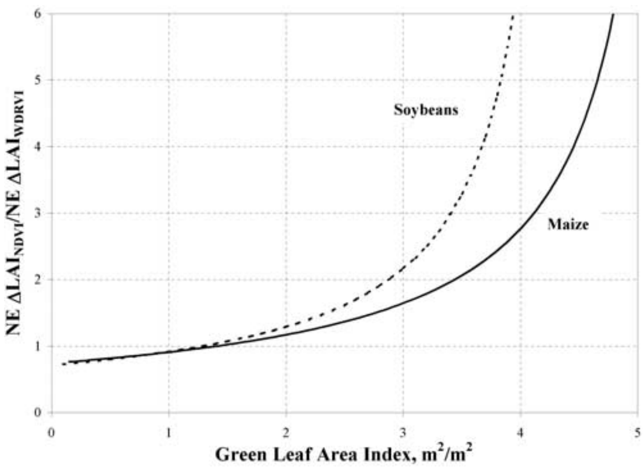

Figure 4. Ratio of noise equivalent of leaf area index (LAI) of MODIS-retrieved NDVI (NE ΔLAI_{NDVI}) and WDRVI (NE ΔLAI_{WDRVI}) plotted versus leaf area index in irrigated and rainfed maize and soybean.

MODIS 250-m data. Since the relationship between LAI and the WDRVI is linear, it is straightforward to invert this relationship between WDRVI and LAI in order to obtain a synoptic measure of green LAI.

4. Conclusions

[16] This study explored the potential of moderate resolution, 250-m MODIS VI data for estimating green LAI in crops. The WDRVI retrieved from the standard MODIS 250-m VI (MOD13Q1) product appeared to be much better proxy of LAI than NDVI, which will allow accurate synoptic estimates of LAI to be made across a wide range of values including moderate-to-high biomass conditions of crops where NDVI loses its sensitivity to changes in LAI. This index can also be obtained from data collected by other satellite-based sensors (e.g., AVHRR, Landsat TM and ETM+, MERIS, SPOT) that have bands in the red and NIR spectral regions. The implications of these findings are far-reaching, since the WDRVI offers a new possibility to more accurately estimate and monitor the LAI of crops from local to global scales using the extensive global archive of MODIS 250-m data that became available in February 2000. With this index and the multi-spectral, time-series data streams from a new era of moderate resolution global imagers such as MODIS and MERIS (Medium Resolution Imaging Spectrometer), it is now possible to obtain global synoptic estimates of LAI in crops with high temporal and spatial resolution. The 250-m spatial resolution and high repeat cycle of these instruments provide the data needed to monitor and characterize crop conditions of agricultural fields across large geographic areas, which was not possible with previous sensors such as Landsat and AVHRR due to their resolution limitations and/or data availability, cost, and quality issues. This study is, to the best of our knowledge, the first to report on the quantitative retrieval of biophysical characteristics of crops from 250-m MODIS data and the results from this work, represent the initial stage in developing more accurate methods to characterize large-area crop conditions.

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