Abstract: Satellite remote sensing estimates of Gross Primary Production (GPP) have routinely been made using spectral Vegetation Indices (VIs) over the past two decades. The Normalized Difference Vegetation Index (NDVI), the Enhanced Vegetation Index (EVI), the green band Wide Dynamic Range Vegetation Index (WDRVIgreen), and the green band Chlorophyll Index (CIgreen) have been employed to estimate GPP under the assumption that GPP is proportional to the product of VI and photosynthetically active radiation (PAR) (where VI is one of four VIs: NDVI, EVI, WDRVIgreen, or CIgreen). However, the empirical regressions between VI*PAR and GPP measured locally at flux towers do not pass through the origin (i.e., the zero X-Y value for regressions). Therefore they are somewhat difficult to interpret and apply. This study investigates (1) what are the scaling factors and offsets (i.e., regression slopes and intercepts) between the fraction of PAR absorbed by chlorophyll of a canopy (fAPARchl) and the VIs, and (2) whether the scaled VIs developed in (1) can eliminate the deficiency and improve the accuracy of GPP estimates. Three AmeriFlux maize and soybean fields were selected for this study, two of which are irrigated and one is rainfed. The four VIs and fAPARchl of the fields were computed with the MODerate resolution Imaging Spectroradiometer (MODIS) satellite images. The GPP estimation performance for the scaled VIs was compared to results obtained with the original VIs and evaluated with standard statistics: the coefficient of determination (R²), the root mean square error (RMSE), and the coefficient of variation (CV). Overall, the scaled EVI obtained the best performance. The performance of the scaled NDVI, EVI and WDRVIgreen was improved across sites, crop types and soil/background wetness conditions. The scaled CIgreen did not improve results, compared to the original CIgreen. The scaled green band indices (WDRVIgreen, CIgreen) did not exhibit superior performance to either the scaled EVI or NDVI in estimating crop daily GPP at these agricultural fields. The scaled VIs are more physiologically meaningful than original un-scaled VIs, but scaling factors and offsets may vary across crop types and surface conditions.
Highlights

• Scale factor and offset are derived with linear regression of fAPAR_{chl} vs. VI
• Scaled NDVI, EVI and WDRVI_{green} improve performance
• Scaled EVI exhibits the best performance
• Scale factor and offset vary with crop types and surface conditions
Estimation of crop gross primary production (GPP):

II. Do scaled MODIS vegetation indices improve performance?

Qingyuan Zhang\textsuperscript{1,2}, Yen-Ben Cheng\textsuperscript{3,2}, Alexei I. Lyapustin\textsuperscript{4}, Yujie Wang\textsuperscript{5,2}, Xiaoyang Zhang\textsuperscript{6}, Andrew Suyker\textsuperscript{7}, Shashi Verma\textsuperscript{7}, Yanmin Shuai\textsuperscript{8}, Elizabeth M. Middleton\textsuperscript{2}

\textsuperscript{1}Universities Space Research Association, Columbia, MD 21044, USA
\textsuperscript{2}Biospheric Sciences Laboratory, National Aeronautics and Space Administration/Goddard Space Flight Center, Greenbelt, MD 20771, USA
\textsuperscript{3}Sigma Space Corporation, Lanham, MD 20706, USA
\textsuperscript{4}Climate and Radiation Laboratory, Code 613, National Aeronautics and Space Administration Goddard Space Flight Center, Greenbelt, MD 20771, USA
\textsuperscript{5}Goddard Earth Sciences and Technology Center, University of Maryland Baltimore County, Baltimore, MD 21228, USA
\textsuperscript{6}Geospatial Sciences Center of Excellence, South Dakota State University, Brookings, SD 57007, USA
\textsuperscript{7}School of Natural Resources, University of Nebraska—Lincoln, Lincoln, NE 68588, USA
\textsuperscript{8}Earth Resources Technology, Inc., Laurel, MD 20707, USA

Corresponding author:

Qingyuan Zhang

Address:

Building 33, Room G317
Biospheric Sciences Laboratory, Code 618,
NASA/Goddard Space Flight Center,
Greenbelt, Maryland 20771, USA

Email: qyz72@yahoo.com
Abstract – Satellite remote sensing estimates of Gross Primary Production (GPP) have routinely been made using spectral Vegetation Indices (VIs) over the past two decades. The Normalized Difference Vegetation Index (NDVI), the Enhanced Vegetation Index (EVI), the green band Wide Dynamic Range Vegetation Index (WDRVI\textsubscript{green}), and the green band Chlorophyll Index (CI\textsubscript{green}) have been employed to estimate GPP under the assumption that GPP is proportional to the product of VI and photosynthetically active radiation (PAR) (where VI is one of four VIs: NDVI, EVI, WDRVI\textsubscript{green}, or CI\textsubscript{green}). However, the empirical regressions between VI*PAR and GPP measured locally at flux towers do not pass through the origin (i.e., the zero X-Y value for regressions). Therefore they are somewhat difficult to interpret and apply. This study investigates (1) what are the scaling factors and offsets (i.e., regression slopes and intercepts) between the fraction of PAR absorbed by chlorophyll of a canopy (fAPAR\textsubscript{chl}) and the VIs, and (2) whether the scaled VIs developed in (1) can eliminate the deficiency and improve the accuracy of GPP estimates. Three AmeriFlux maize and soybean fields were selected for this study, two of which are irrigated and one is rainfed. The four VIs and fAPAR\textsubscript{chl} of the fields were computed with the MODerate resolution Imaging Spectroradiometer (MODIS) satellite images. The GPP estimation performance for the scaled VIs was compared to results obtained with the original VIs and evaluated with standard statistics: the coefficient of determination ($R^2$), the root mean square error (RMSE), and the coefficient of variation (CV). Overall, the scaled EVI obtained the best performance. The performance of the scaled NDVI, EVI and WDRVI\textsubscript{green} was improved across sites, crop types and soil/background wetness conditions. The scaled CI\textsubscript{green} did not improve results, compared to the original CI\textsubscript{green}. The scaled green band indices (WDRVI\textsubscript{green}, CI\textsubscript{green}) did not exhibit superior performance to either the scaled EVI or NDVI in estimating crop daily GPP at these agricultural fields. The scaled VIs are more physiologically meaningful than
original un-scaled VIs, but scaling factors and offsets may vary across crop types and surface conditions.

Key Words – Daily GPP, MODIS, Vegetation Index, fAPAR<sub>chl</sub>

I. INTRODUCTION

Atmospheric general circulation models require quantification of land-atmosphere exchanges of energy, water and momentum, including CO<sub>2</sub> fluxes which can be provided by land surface process models (Bonan et al., 2011; Dickinson et al., 1993; Sellers et al., 1986). Satellite remote sensing offers inputs such as land cover types and the Normalized Difference Vegetation Index (NDVI) (Deering, 1978; Tucker, 1979) for use in the land surface modeling (Dickinson et al., 1990; Sellers et al., 1994). Pioneering work (Asrar et al., 1992; Myneni et al., 1997; Running et al., 2000; Sellers, 1987) has shown the fraction of photosynthetically active radiation (PAR) absorbed by a canopy/vegetation (FPAR, i.e., fAPAR<sub>canopy</sub>) can be approximated with NDVI (Running et al., 2000). Therefore, NDVI has been employed to estimate vegetation Gross Primary Productivity (GPP) in a variation (as GPP=ε*NDVI*PAR, Running et al., 2000), inspired by the logic from the Light Use Efficiency (LUE) model (Monteith, 1972, 1977):

\[
GPP = \varepsilon \ast fAPAR_{PSN} \ast PAR = \varepsilon \ast APAR_{PSN},
\]

where ε is LUE for vegetation photosynthesis (PSN) (Running et al., 2000) and fAPAR<sub>PSN</sub> is the fraction of PAR absorbed for PSN (APAR<sub>PSN</sub>). Monitoring changes in crop GPP with satellite remote sensing data advances the capability to understand and manage global food security, sustainability practices, and environmental impacts, and to study global carbon cycle and global water cycle.
The three-band Enhanced Vegetation Index (EVI) (Huete et al., 1997) and the two-band EVI (called EVI2, Jiang et al., 2008) have also been utilized to predict terrestrial GPP in a similar way as $\text{GPP} = \varepsilon \cdot \text{EVI} \cdot \text{PAR}$ (Jin et al., 2013; Kalfas et al., 2011; King et al., 2011; Li et al., 2007; Mahadevan et al., 2008; Schubert et al., 2012; Sjöström et al., 2011; Wu et al., 2008, 2010, 2011, 2012; Xiao et al., 2004; Yan et al., 2009). In addition, Gitelson and colleagues also explored the application of the green band Wide Dynamic Range Vegetation Index (WDRVI\text{green}) and the green band Chlorophyll Index (CI\text{green}) for crop GPP estimation, in addition to the NDVI and EVI (Gitelson et al., 2008, 2012; Peng and Gitelson, 2011, 2012; Peng et al., 2011).

However, since the empirical regressions between the VI*PAR products and GPP measured locally at flux towers do not pass through the origin (i.e., the zero X-Y value for regressions) and produce offsets, they are somewhat difficult to interpret and apply (Gitelson et al., 2012; Sims et al., 2006; Zhang et al., 2014b). This is considered to be a source of error affecting the accuracy and reliability of remote sensing GPP estimates based on VIs. In the literature, there is no paper that presents how to scale the VIs in space and time to solve the problem.

The standard MODerate resolution Imaging Spectroradiometer (MODIS) 8-day GPP product (MOD17A2 GPP) uses the MOD15A2 FPAR (a fAPAR\text{canopy}) product as a model input (Running et al., 2004; Zhao and Running, 2008). Investigations to find the scaling factor and offset of NDVI through $\text{fAPAR}_{\text{canopy}} - \text{NDVI}$ functions have been conducted, where $\text{fAPAR}_{\text{canopy}} = a_0 \cdot \text{NDVI} + b_0$ ($a_0$ is the scaling factor or slope, and $b_0$ is y intercept or offset) (Fensholt et al., 2004; Goward and Huemmrich, 1992; Knyazikhin et al., 1998, 2002; Potter et al., 1993; Prince and Goward, 1995; Randerson et al., 1996; Sellers et al., 1996; Sims et al., 2005). However, the MOD15A2 FPAR product overestimates in-situ $\text{fAPAR}_{\text{canopy}}$ during spring greenup and fall
senescent periods, and underestimates in-situ fAPAR\textsubscript{canopy} in mid-summer during peak GPP activity at the agricultural fields we selected [see (Zhang et al., 2014a) for details].

We developed an algorithm to retrieve the fraction of PAR absorbed by chlorophyll throughout the canopy (fAPAR\textsubscript{chl}) from actual MODIS observations or from synthesized 30 m MODIS-spectral-like observations simulated with EO-1 Hyperion images (Zhang, 2003; Zhang et al., 2005, 2009, 2012, 2013, 2014c). We found that fAPAR\textsubscript{chl} ≠ fAPAR\textsubscript{canopy}, and that the fraction of PAR absorbed by foliage non-chlorophyll components (fAPAR\textsubscript{non-chl}) varies with types and seasonally (Zhang et al., 2013). Zhang et al. (2014a) presented the performance of fAPAR\textsubscript{chl} and MOD15A2 FPAR in crop GPP estimation, and concluded that fAPAR\textsubscript{chl} is superior to MOD15A2 FPAR. Zhang et al. (2014b) investigated the performance of original un-scaled VIs in GPP estimation, and suggested that further investigation on the performance of scaled VIs should be carried out.

The objectives of this paper are straightforward: 1] to explore how surface conditions affect the scaling factors (“a”) and offsets (“b”) derived through regression analysis of fAPAR\textsubscript{chl} vs. the four VIs: fAPAR\textsubscript{chl} = a*VI+b for each crop type (corn, soybean) per field; 2] to investigate how much the scaled VIs can improve the prediction accuracy of GPP estimates compared to the prediction of original un-scaled VIs.

II. METHODS

II.1 Study sites and tower data

The three AmeriFlux crop sites for corn, or maize (Zea mays L.) and soybean (Glycine max [L.] Merr.) used in this study are located at the University of Nebraska–Lincoln (UNL)
Agricultural Research and Development Center near Mead, Nebraska (US-NE1, US-NE2 and US-NE3). The first two fields are circular (radius ~ 390 m) and equipped with center-pivot irrigation systems (US-NE1, 41°09’54.2”N, 96°28’35.9”W; US-NE2, 41°09’53.6”N, 96°28’07.5”W). The third is a 790 m long square field (US-NE3, 41°10’46.7”N, 96°26’22.4”W) that relies entirely on rainfall. Each field is equipped with an eddy covariance flux tower (Gitelson et al., 2012; Gitelson et al., 2006; Peng et al., 2013). The first field (US-NE1) is a continuous maize field while the other two fields are maize-soybean rotation fields (soybean is planted in even years).

Tower eddy-covariance carbon exchange, PAR, and GPP measurements in growing season from 2001-2006 are publically available and can be downloaded from ftp://cdiac.ornl.gov/pub/ameriflux/data. The nighttime ecosystem respiration/temperature Q_{10} relationship was used to estimate the daytime ecosystem respiration (Baldocchi, 2003). Daily GPP was computed by subtracting respiration (R) from net ecosystem exchange (NEE), i.e.,

\[ \text{GPP} = \text{NEE} - \text{R} \]  

(Suyker et al., 2005). These sites provided the opportunity to examine the semi-empirical relationships between fAPAR_{chl} versus VIs for both C4 (maize) and C3 (soybean) crops in both irrigated and non-irrigated ecosystems, and to investigate the benefits of employing the scaled relationships to estimate GPP.

II.2 Remote sensing data processing and GPP estimation

Six years (2001-2006) of MODIS L1B calibrated radiance data (MOD021KM and MOD02HKM) and geolocation data (MOD03) covering the three study sites were downloaded from https://ladsweb.nascom.nasa.gov:9400/data/. Two of the MODIS bands have a nadir spatial resolution of 250 m: B1 (red, 620 – 670 nm) and B2 (near infrared, NIR, 841 – 876 nm). The MODIS land bands 3 - 7 have a nadir spatial resolution of 500 m: B3 (blue, 459 – 479 nm), B4
(green, 545 – 565 nm), B5 (NIR2, 1230 – 1250 nm), B6 (shortwave infrared, SWIR1, 1628 –
1652 nm) and B7 (SWIR2, 2105 – 2155 nm). The centers of the original 500 m grids defined in
the standard surface reflectance product (MOD09) that encompass the three tower sites are not
the centers of the three fields and vegetation in each of the original 500 m grids is not
homogeneous [see Figure 2 of (Guindin-Garcia et al., 2012)]. The MODIS gridding procedure
for the standard MOD09 product does not ensure the gridded surface reflectance covers the
entire grid (Wolfe et al., 1998). A modified gridding procedure was used for this study (Zhang et
al., 2014b), whereby the centers of the three 500 m grids were matched to the centers of the three
fields, respectively. The L1B radiance data from each swath were gridded at 500 m resolution for
MODIS bands 1-7 with area weight of each MODIS observation. This modified gridding
processing was incorporated into the Multi-Angle Implementation of Atmospheric Correction
(MAIAC) algorithm (Lyapustin et al., 2008, 2011a, b, 2012). MAIAC is an advanced algorithm
which uses time series analysis and a combination of pixel-based and image-based processing to
improve cloud/snow detection, and to achieve more accurate aerosol retrievals and atmospheric
correction, based on the bidirectional reflectance distribution function (BRDF) model of the

Derived bidirectional reflectance factors (BRF, also called directional surface reflectance)
in MODIS bands 1-7 were used for this study. The impact of MODIS observation footprint size
resulting from variable view zenith angle (VZA) on crop daily GPP estimation for these sites
was recently reported elsewhere (Zhang et al., 2014b). In order to eliminate the potential bias due
to large VZAs, only observations with VZA ≤ 35° were included in this study. The surface
reflectance data (ρ) were used to calculate the following indices (Deering, 1978; Gitelson, 2004;
Gitelson et al., 2007, 2012; Huete et al., 1997, 2002; Tucker, 1979):

7
\[ CI_{\text{green}} = \frac{\rho_{NIR_1}}{\rho_{\text{green}}} - 1 \]  
\[ WDRVI_{\text{green}} = \frac{0.3\rho_{NIR_1} - \rho_{\text{green}}}{0.3\rho_{NIR_1} + \rho_{\text{green}}} + \frac{1-0.3}{1+0.3} \]  
\[ NDVI = \frac{\rho_{NIR_1} - \rho_{\text{red}}}{\rho_{NIR_1} + \rho_{\text{red}}} \]  
\[ EVI = 2.5 \frac{\rho_{NIR_1} - \rho_{\text{red}}}{1+\rho_{NIR_1}+6\rho_{\text{red}}-7.5\rho_{\text{blue}}} \]

We used the PROSAIL2 model (Jacquemoud and Baret, 1990; Baret and Fourty, 1997; Braswell et al., 1996; Verhoef, 1984, 1985; Zhang et al., 2005, 2009, 2012, 2013), a coupled soil-canopy-leaf radiative transfer model, to retrieve fAPAR$_{\text{chl}}$, the fraction of PAR absorbed by the foliage of the canopy (fAPAR$_{\text{foliage}}$), and the fraction of PAR absorbed by the non-photosynthetic foliage components (fAPAR$_{\text{non-chl}}$)(Zhang et al., 2014a). A pixel is composed of canopy and soil (Zhang et al., 2009, 2012, 2013). The canopy is partitioned into foliage and stem (including branch), and the foliage component is further partitioned into chlorophyll (chl) and non-chlorophyll (non-chl) components, where non-chl is composed of non-photosynthetic pigments (referred to as brown pigment) and dry matter (Baret and Fourty, 1997). The surface reflectances of MODIS bands 1 – 7 are used for retrieval of fAPAR variables (Zhang et al., 2009, 2012, 2013, 2014c):

\[ fAPAR_{\text{non-chl}} = fAPAR_{\text{brown pigment}} + fAPAR_{\text{dry matter}} \]  
\[ fAPAR_{\text{foliage}} = fAPAR_{\text{chl}} + fAPAR_{\text{non-chl}} \]  
\[ fAPAR_{\text{canopy}} = fAPAR_{\text{foliage}} + fAPAR_{\text{stem}} \]
The scaling factors (“a”) and offsets (“b”) of VIs were derived from linear regression through fAPAR_{chl} – VI functions for each crop type per field, where fAPAR_{chl} = a*VI + b (VIs=NDVI, EVI, WDRVI\textsubscript{green}, and CI\textsubscript{green}).

The product of VIs and tower daily PAR (VI*PAR) and the product of scaled VIs and daily PAR (scaled VI*PAR) were compared against the tower daily GPP for each crop type per field (GPP=\bar{c}\cdot VI*PAR or GPP=\bar{c}*scaled VI*PAR). The coefficients “\bar{c}_0” and “\bar{c}” were computed with a least squares best fit algorithm. The computed values for \bar{c}_0 and \bar{c} were then used to predict GPP, and coefficient of determination (R^2), the root mean square error (RMSE, g C m^{-2} d^{-1}) and coefficient of variation (CV, %) was calculated. The average light use efficiency at chlorophyll level (LUE_{chl}, i.e., \overline{\varepsilon_{chl}}) was computed using GPP=LUE_{chl}\cdot fAPAR_{chl}\cdot PAR with a least squares best fit algorithm. Improvements of crop daily GPP estimation using scaled VIs were assessed.

III. RESULTS

The scaling factor (“a”, also called slope) and offset (“b”, also called y-intercept) obtained through the regression functions fAPAR_{chl} =a*VI+b for each crop per field are listed in Table 1, where the statistics for the R^2, RMSE and x-intercept are also summarized. The x-intercepts of fAPAR_{chl} =a*VI+b give minimum VI values at zero fAPAR_{chl}. The 95% confidence intervals of slope, y-intercept and x-intercept for each crop per field are reported, too. The CI_{green} is a simple ratio index while the other three VIs include consideration of normalization. The confidence intervals for CI_{green} are different from those for other three VIs for each type per field.

For each crop type in irrigated fields USNE1 and USNE2, the confidence intervals of y-intercepts and x-intercepts for NDVI, EVI and CI_{green} are different from each other. For each
crop type in rainfed field USNE3, the confidence intervals of y-intercepts and x-intercepts for
NDVI and CI\textsubscript{green} overlap each other, but are different from those for EVI. Mean values of the
confidence intervals of the slopes, y-intercepts and x-intercepts vary with VIs, sites, crop types
and irrigation options. None of the y-intercepts or x-intercepts for NDVI, EVI or WDRVI\textsubscript{green} is
close to the origin (i.e., zero X-Y point).

The functions in Tab. 1 were used to compute the scaled values of NDVI, EVI,
WDRVI\textsubscript{green} and CI\textsubscript{green} for each crop type per field. For instance, for the NDVI at US-NE1:
scaled NDVI = 1.11*NDVI-0.29. The coefficients $\varepsilon_0$ and $\varepsilon$ and LUE\textsubscript{chl} of each crop per field are
listed in Table 2. Corn LUE\textsubscript{chl} is ~1.6 times of soybean LUE\textsubscript{chl} (Tab. 2), which agrees with the
expectation that C4 plants have higher LUE than C3 plants (e.g., Prince, 1991), and explains why
maize displays a wider daily GPP range (~34 g C m\textsuperscript{-2} d\textsuperscript{-1}) than soybean (~19 g C m\textsuperscript{-2} d\textsuperscript{-1})(Zhang
et al., 2014b). The coefficients $\varepsilon_0$ and $\varepsilon$ were applied to estimate crop daily GPP.

Figure 1 shows the estimated soybean daily GPP for the rainfed field US-NE3 using the
four original VIs with $\varepsilon_0$ and the scaled VIs with $\varepsilon$, compared to tower daily GPP. The scaled
NDVI, EVI and WDRVI\textsubscript{green} combined with $\varepsilon$ had better GPP estimation performance than the
original counterparts, respectively, demonstrating higher $R^2$ and lower RMSE. Compared to the
original counterparts, the (scaled NDVI)*PAR, the (scaled EVI)*PAR and the (scaled
WDRVI\textsubscript{green})*PAR values were closer to 0 when GPP=0. The scaled CI\textsubscript{green} did not provide
better GPP estimation than the original CI\textsubscript{green}. In order to save pages, similar figures for US-NE1,
US-NE2 and figures for maize in US-NE3 are not presented in this paper.

Table 3 summarized the statistics ($R^2$, RMSE and CV) for estimating crop daily GPP
using the original VIs with $\varepsilon_0$ and the scaled VIs with $\varepsilon$, respectively. These statistics show that
the best performance was obtained with the scaled EVI while the least successful performance
among the four scaled VIs was obtained with CI\textsubscript{green} across the sites, crop types and irrigation/
irrigated options. For example at the US-NE1 site, scaled EVI and scaled CI\textsubscript{green} had contrasting
best/worst performances in GPP estimation: \( R^2: 0.88 / 0.77 \), \( \text{RMSE}: 2.92 / 4.05 \text{ g C m}^{-2} \text{ d}^{-1} \), and
\( \text{CV}: 19\% / 26\% \) (Tab. 3). GPP estimates for corn had better performance than for soybean using
scaled NDVI and EVI for sites US-NE2 and US-NE3. Better results might be achieved for the
sites examined in other studies (King et al., 2011; Sjöström et al., 2009) if the scaled EVI
(through coefficients obtained from the regression of fAPAR\textsubscript{chl} vs. EVI) had been utilized.

For each crop in any field, the scaled NDVI, EVI and WDRVI\textsubscript{green} improved the
prediction performance of crop daily GPP while the scaled CI\textsubscript{green} did not, compared to the
original un-scaled VIs. GPP improvements for the three that benefited from scaling, ranked from
most to least were the NDVI, WDRVI\textsubscript{green}, EVI, for which the \( R^2 \) increased (\( \uparrow: 0.16, 0.13, 0.09 \)),
\( \text{RMSE} \) decreased (\( \downarrow: 0.95, 0.78, 0.65 \text{ g C m}^{-2} \text{ d}^{-1} \)), and the \( \text{CV} \) also decreased (\( \downarrow: 8\%, 6\%, 5\% \)).
The improvements also varied with crop types and irrigation conditions. For example, the NDVI
improvement for soybean (\( R^2, \uparrow 0.20; \text{CV, \downarrow 9\%} \)) was better than for corn (\( R^2, \uparrow 0.13; \text{CV, \downarrow 7\%} \)),
and the average improvement for the irrigated field (\( R^2, \uparrow 0.21; \text{RMSE, \downarrow 1.10 \text{ g C m}^{-2} \text{ d}^{-1} \}; \text{and CV, \downarrow 10\% \}} \) was better than for the irrigation fields (\( R^2, \uparrow 0.12; \text{RMSE, \downarrow 0.85 \text{ g C m}^{-2} \text{ d}^{-1} \}; \text{and CV, \downarrow 6\%} \)).

IV. DISCUSSION
The PSROAIL2 model well distinguishes vegetation from soil and fAPAR\textsubscript{chl} retrieved
with the PROSAIL2 model excludes the impact of soil/background (Zhang et al., 2012, 2013).
The \( f_{\text{APAR}} \) foliage comprises chlorophyll and non-chlorophyll foliage fractions (\( f_{\text{APAR}_{\text{chl}}} \), \( f_{\text{APAR}_{\text{non-chl}}} \)). Therefore, the PAR absorbed by non-photosynthetic vegetation components (NPV) of the canopy is excluded from \( \text{APAR}_{\text{chl}} \) since \( \text{APAR}_{\text{chl}} = f_{\text{APAR}_{\text{chl}}} \times \text{PAR} \). This is the theoretical basis for potential improvement of GPP estimation using the scaled VIs. The x-intercept values of the semi-empirical linear functions of \( f_{\text{APAR}_{\text{chl}}} \) vs. VI in Table 1 have an important biophysical meaning: there is not any chlorophyll showing up at the pixel when its un-scaled VI is less than its x-intercept value. Gitelson and colleagues (Gitelson et al., 2007) reported that, before green-up when green leaves do not appear, MODIS 250 m NDVI values for the fields could be greater than 0.2, which is close to the minimum x-intercepts of NDVI (0.23, Tab. 1) we found with MODIS 500 m images. In irrigated fields, the mean values of the x-intercept confidence intervals for EVI were about half of those for NDVI, and about 1/3 as large as those for \( \text{WDRVI}_{\text{green}} \) (Tab. 1). In rainfed fields, the mean values of the x-intercept confidence intervals for EVI were about half of those for both NDVI and \( \text{WDRVI}_{\text{green}} \) (Tab. 1). Soil/background wetness has less impact on EVI than on NDVI which is consistent with the original idea that inspired the development of EVI (Huete, 1988; Huete et al., 1997). Daughtry et al. (2000) has expressed that VIs combined with NIR and red bands are less impacted by background than VIs combined with NIR and green bands. Earlier studies (Sims et al., 2006, 2008) have shown that GPP drops to zero at variable EVI values (i.e., x-intercept EVI values) in their selected flux sites, and have found the minimum x-intercept value is \(~0.1\). So Sims et al. (2008) has developed a GPP model using \( \text{EVI} - 0.1 \) instead of the original EVI. The x-intercept confidence intervals of EVI in the three fields (US-NE1, US-NE2 and US-NE3) ranged from (0.12, 0.13), (0.14, 0.15) to (0.16, 0.18). Our findings are consistent with earlier empirical studies (Daughtry et al., 2000; Huete, 1988; Huete et al., 1997; Sims et al., 2006, 2008). Furthermore,
the scaled VIs with scaling factors and offsets using the semi-empirical relationships between 
fAPAR_{chl} vs. VIs for each crop type per field are more physiologically meaningful (Tab. 1) than 
the original un-scaled VIs.

The $\bar{e}$ estimates for all scaled VIs are close to the relevant $\text{LUE}_{chl}$ values for each crop 
type per field. In contrast, the $\bar{e}_0$ estimates associated with the original un-scaled NDVI and 
WDRVI_{green} are lower than the relevant $\text{LUE}_{chl}$ values. The $\bar{e}_0$ estimates for CI_{green} are much 
lower than the relevant $\text{LUE}_{chl}$ values because the original un-scaled CI_{green} range (~1 to 10) is 
much wider than the scaled CI_{green} range (~0 to ~1). It is worth noting that both the $\bar{e}_0$ and the $\bar{e}$ 
estimates for the original EVI and the scaled EVI are close to the physiologically relevant $\text{LUE}_{chl}$ 
values. This partly explains the reasonableness and success of the Vegetation Photosynthesis 
Model (VPM) (Xiao et al., 2004) which assumes $\text{GPP}=e^{*}\text{EVI}^{*}\text{PAR}$. This study suggests that the 
GPP estimation made with the VPM may be improved by replacing the original EVI with 
fAPAR_{chl}, or by scaling the EVI using the relationship between fAPAR_{chl} and EVI.

The $R^2$ between tower daily GPP and estimated GPP with scaled VIs for all cases ranges 
from 0.66 to 0.88 while the RMSE (CV) between them ranges from 4.37 to 2.11 g C m$^{-2}$ d$^{-1}$ 
(from 31% to 17%). Although the $R^2$ between fAPAR_{chl} and scaled VI is high for all cases (0.73 
– 0.97), the RMSE between fAPAR_{chl} and scaled VI varies with crop type, irrigation/rainfed 
options, and VI options, which caused the variation of the performance of estimated GPP with 
scaled VIs. Among the four scaled VIs, the RMSE between fAPAR_{chl} and the scaled EVI is 
smallest and the $R^2$ is highest for all study sites. For US-NE2 and US-NE3, the RMSE between 
fAPAR_{chl} and scaled CI_{green} is biggest and the $R^2$ is lowest.
This study exhibited improvement in the performance of crop daily GPP estimation using scaled NDVI, EVI and WDRVI_{green}, compared to their original un-scaled counterparts. However, performance improvement of crop daily GPP estimation using scaled CI_{green} was not observed. The irrigated fields have better performance, as compared to the rainfed field. The performance also varied with crop types and VI options. The scaled EVI provided the best performance among all cases. This study does not find that the scaled WDRVI_{green} or the scaled CI_{green} is superior to the scaled NDVI or scaled EVI in predicting crop daily GPP.

Compared to the original VIs, the scaled VIs developed with the semi-empirical relationships between fAPAR_{chl} and VIs are more physiologically meaningful. However, the scaling factors and offsets (and x-intercepts) vary field by field, and vary type by type. Investigations to explore the scaling factors and offsets of these VIs using fAPAR_{chl} for other plant functional types should be carried out in the future. We will explore how the scaling factors and offsets change over space and time, and vary with climate. Investigations on whether scaled EVI is best for all fields and all types among the four scaled VIs are also needed. We suggest an approach whereby MODIS-derived VIs are scaled pixel by pixel. This approach provides scaled VIs for use when fAPAR_{chl} is unavailable. We expect that future research on GPP simulation based on the biochemical or land surface modeling (Bounoua et al., 2000; Potter et al., 2003; Sellers et al., 1994, 1996) will achieve reduced uncertainty and improved accuracy when the scaled MODIS VIs replace the original VIs.

ACKNOWLEDGMENTS
This study was supported by NASA Terrestrial Ecology project (Grant No., NNX12AJ51G; PI, Q. Zhang) and NASA Science of Terra and Aqua project (Grant No., NNX14AK50G; PI, Q. Zhang) (Dr. Diane Wickland, manager). We would like to thank the support and the use of facilities and equipment provided by the Center for Advanced Land Management Information Technologies and the Carbon Sequestration program, University of Nebraska–Lincoln. Site-specific climate and CO₂ flux data are distributed by AmeriFlux network (http://public.ornl.gov/ameriflux), supported by Carbon Dioxide Information Analysis Center at the Oak Ridge National Laboratory of the Department of Energy. We are grateful to anonymous reviewers whose comments helped improve the paper.

References:


Goldstein, A.H., Hollinger, D.Y., Misson, L., Monson, R.K., Oechel, W.C., Schmid, H.P.,
productivity of North American ecosystems. *Journal of Geophysical Research, 111*, 1-16

production estimates in a sparse savanna in the Sudan. *Biogeosciences, 6*, 129-138

Kutsch, W.L., Merbold, L., Nouvellon, Y., Scholes, R.J., Schubert, P., Seaquist, J., &

ecosystem respiration of irrigated maize and irrigated soybean during a growing season.
*Agricultural and Forest Meteorology, 131*, 180-190


Sensing of Environment, 17*, 165–178

Wolfe, R., Roy, D., & Vermote, E. (1998). The MODIS land data storage, gridding and
compositing methodology: Level 2 Grid. *IEEE Transactions on Geosciences and Remote
Sensing, 36*, 1324-1338

Staebler, R.M. (2012). Remote sensing of canopy light use efficiency in temperate and
boreal forests of North America using MODIS imagery. *Remote Sensing of Environment,
118*, 60-72

Sens. Environ., 115*, 3424-3435

Wu, C., Niu, Z., & Gao, S. (2010). Gross primary production estimation from MODIS data with
vegetation index and photosynthetically active radiation in maize. *Journal of Geophysical
Research, 115*, 1-12

production of a temperate grassland ecosystem in Inner Mongolia, China, using MODIS
imagery and climate data. *Science in China Series D: Earth Sciences, 51*, 1-12

Satellite-based modeling of gross primary production in an evergreen needleleaf forest.
*Rem. Sens. Environ., 89*, 519-534

productivity for winter wheat–maize double cropping system using MODIS time series
and CO2 eddy flux tower data. *Agriculture, Ecosystems and Environment, 129*, 391-400

of fraction of photosynthetically active radiation absorbed by chlorophyll (fAPARchl)
versus FAPAR. *NASA Earth System Science (ESS) Fellowship Program*
Figure captions

Figure 1. Comparison between tower daily GPP vs. estimated daily GPP for the US-NE3 site (soybean): (a) NDVI; (b) EVI; (c) WDRVI_{green}; and (d) CI_{green}. Filled circles use original unscaled VIs while empty circles use scaled VIs. Only observations with VZA ≤ 35° are included.

Table captions

Table 1. List of relationships between fAPAR_{chl} and VIs for the three crop sites (y=ax+b, y:fAPAR_{chl}, x:VI). The 95% confidence intervals of slope (“a”), y-intercept (“b”), and x-intercept are presented. Coefficients of determination (R^2) and root mean square error (RMSE) are also presented.

Table 2. List of the coefficient \( \bar{e}_0 \) in \( GPP=\bar{e}_0 \cdot VI \cdot PAR \), the coefficient \( \bar{e} \) in \( GPP=\bar{e} \cdot scaled \ VI \cdot PAR \), and LUE_{chl} in \( GPP=LUE_{chl} \cdot fAPAR_{chl} \cdot PAR \) (unit: g C mol^{-1} PPFD)

Table 3. Coefficients of determination (R^2), root mean square errors (RMSE, g C m^{-2} d^{-1}) and coefficients of variation (CV) for simulated GPP with the VIs using two options: original unscaled VIs versus scaled VIs, compared to tower daily GPP
Figure 1. Comparison between tower daily GPP vs. estimated daily GPP for the US-NE3 site (soybean): (a) NDVI; (b) EVI; (c) WDRVI\textsubscript{green}; and (d) CI\textsubscript{green}. Filled circles use original unscaled VIs while empty circles use scaled VIs. Only observations with VZA ≤ 35° are included.
Table 1. List of relationships between fAPAR<sub>chl</sub> and VIs for the three crop sites (y=ax+b, y:fAPAR<sub>chl</sub>, x:VI). The 95% confidence intervals of slope (“a”), y-intercept (“b”), and x-intercept are presented. Coefficients of determination ($R^2$) and root mean square error (RMSE) are also presented.

<table>
<thead>
<tr>
<th>Site</th>
<th>Function</th>
<th>NDVI</th>
<th>EVI</th>
<th>WDRVI&lt;sub&gt;green&lt;/sub&gt;</th>
<th>CI&lt;sub&gt;green&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>US-NE1 (maize, irrigated)</td>
<td>$y=1.11x-0.29$</td>
<td>$y=1.30x-0.18$</td>
<td>$y=1.13x-0.39$</td>
<td>$y=0.13x-0.13$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>slope 95% confidence interval</td>
<td>(1.07, 1.14)</td>
<td>(1.26, 1.34)</td>
<td>(1.09, 1.17)</td>
<td>(0.12, 0.13)</td>
</tr>
<tr>
<td></td>
<td>y intercept 95% confidence interval</td>
<td>(-0.31, -0.27)</td>
<td>(-0.20, -0.17)</td>
<td>(-0.41, -0.37)</td>
<td>(-0.14, -0.11)</td>
</tr>
<tr>
<td></td>
<td>x intercept 95% confidence interval</td>
<td>(0.26, 0.27)</td>
<td>(0.14, 0.15)</td>
<td>(0.34, 0.35)</td>
<td>(0.92, 1.04)</td>
</tr>
<tr>
<td></td>
<td>$R^2$</td>
<td>0.95</td>
<td>0.96</td>
<td>0.94</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>RMSE</td>
<td>0.06</td>
<td>0.05</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>US-NE2 (maize, irrigated)</td>
<td>$y=1.10x-0.27$</td>
<td>$y=1.29x-0.16$</td>
<td>$y=1.11x-0.37$</td>
<td>$y=0.12x-0.10$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>slope 95% confidence interval</td>
<td>(1.07, 1.14)</td>
<td>(1.25, 1.34)</td>
<td>(1.07, 1.15)</td>
<td>(0.11, 0.12)</td>
</tr>
<tr>
<td></td>
<td>y intercept 95% confidence interval</td>
<td>(-0.29, -0.25)</td>
<td>(-0.18, -0.15)</td>
<td>(-0.40, -0.35)</td>
<td>(-0.12, -0.08)</td>
</tr>
<tr>
<td></td>
<td>x intercept 95% confidence interval</td>
<td>(0.24, 0.25)</td>
<td>(0.12, 0.13)</td>
<td>(0.33, 0.34)</td>
<td>(0.72, 0.91)</td>
</tr>
<tr>
<td></td>
<td>$R^2$</td>
<td>0.96</td>
<td>0.96</td>
<td>0.95</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>RMSE</td>
<td>0.05</td>
<td>0.05</td>
<td>0.06</td>
<td>0.08</td>
</tr>
<tr>
<td>US-NE2 (soybean, irrigated)</td>
<td>$y=1.06x-0.25$</td>
<td>$y=1.21x-0.16$</td>
<td>$y=1.04x-0.32$</td>
<td>$y=0.11x-0.08$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>slope 95% confidence interval</td>
<td>(1.03, 1.10)</td>
<td>(1.18, 1.24)</td>
<td>(1.00, 1.08)</td>
<td>(0.10, 0.12)</td>
</tr>
<tr>
<td></td>
<td>y intercept 95% confidence interval</td>
<td>(-0.27, -0.23)</td>
<td>(-0.17, -0.14)</td>
<td>(-0.34, -0.30)</td>
<td>(-0.10, -0.06)</td>
</tr>
<tr>
<td></td>
<td>x intercept 95% confidence interval</td>
<td>(0.23, 0.24)</td>
<td>(0.12, 0.13)</td>
<td>(0.30, 0.31)</td>
<td>(0.58, 0.81)</td>
</tr>
<tr>
<td></td>
<td>$R^2$</td>
<td>0.95</td>
<td>0.97</td>
<td>0.94</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>RMSE</td>
<td>0.05</td>
<td>0.05</td>
<td>0.06</td>
<td>0.08</td>
</tr>
<tr>
<td>US-NE3 (maize, rainfed)</td>
<td>$y=1.25x-0.43$</td>
<td>$y=1.46x-0.25$</td>
<td>$y=1.13x-0.39$</td>
<td>$y=0.11x-0.02$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>slope 95% confidence interval</td>
<td>(1.12, 1.38)</td>
<td>(1.34, 1.59)</td>
<td>(1.00, 1.26)</td>
<td>(0.10, 0.13)</td>
</tr>
<tr>
<td></td>
<td>y intercept 95% confidence interval</td>
<td>(-0.51, -0.34)</td>
<td>(-0.30, -0.19)</td>
<td>(-0.48, -0.30)</td>
<td>(-0.08, 0.04)</td>
</tr>
<tr>
<td></td>
<td>x intercept 95% confidence interval</td>
<td>(0.33, 0.35)</td>
<td>(0.16, 0.18)</td>
<td>(0.33, 0.36)</td>
<td>(0.05, 0.37)</td>
</tr>
<tr>
<td></td>
<td>$R^2$</td>
<td>0.82</td>
<td>0.87</td>
<td>0.78</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td>RMSE</td>
<td>0.07</td>
<td>0.06</td>
<td>0.07</td>
<td>0.08</td>
</tr>
<tr>
<td>US-NE3 (soybean, rainfed)</td>
<td>$y=1.29x-0.44$</td>
<td>$y=1.37x-0.24$</td>
<td>$y=1.07x-0.35$</td>
<td>$y=0.10x+0.03$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>slope 95% confidence interval</td>
<td>(1.18, 1.40)</td>
<td>(1.28, 1.46)</td>
<td>(0.95, 1.19)</td>
<td>(0.08, 0.11)</td>
</tr>
<tr>
<td></td>
<td>y intercept 95% confidence interval</td>
<td>(-0.52, -0.37)</td>
<td>(-0.29, -0.19)</td>
<td>(-0.44, -0.26)</td>
<td>(-0.04, 0.09)</td>
</tr>
<tr>
<td></td>
<td>x intercept 95% confidence interval</td>
<td>(0.33, 0.36)</td>
<td>(0.17, 0.18)</td>
<td>(0.31, 0.35)</td>
<td>(-0.57, -0.02)</td>
</tr>
<tr>
<td></td>
<td>$R^2$</td>
<td>0.91</td>
<td>0.94</td>
<td>0.85</td>
<td>0.77</td>
</tr>
<tr>
<td></td>
<td>RMSE</td>
<td>0.06</td>
<td>0.05</td>
<td>0.08</td>
<td>0.10</td>
</tr>
</tbody>
</table>
Table 2. List of the coefficient $\bar{\varepsilon}_0$ in GPP=$\bar{\varepsilon}_0*$VI*PAR, the coefficient $\bar{\varepsilon}$ in GPP=$\bar{\varepsilon}$*scaled VI*PAR, and LUE$_{chl}$ in GPP=LUE$_{chl}$*fAPAR$_{chl}$*PAR (unit: g C mol$^{-1}$ PPFD)

<table>
<thead>
<tr>
<th></th>
<th>LUE$_{chl}$</th>
<th>NDVI</th>
<th>EVI</th>
<th>WDRVI$_{green}$</th>
<th>CI$_{green}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\bar{\varepsilon}_0$</td>
<td>$\bar{\varepsilon}$</td>
<td>$\bar{\varepsilon}_0$</td>
<td>$\bar{\varepsilon}$</td>
<td>$\bar{\varepsilon}_0$</td>
</tr>
<tr>
<td>UE-NE1 (corn, irrigated)</td>
<td>0.65</td>
<td>0.48</td>
<td>0.68</td>
<td>0.65</td>
<td>0.67</td>
</tr>
<tr>
<td>US-NE2 (corn, irrigated)</td>
<td>0.65</td>
<td>0.49</td>
<td>0.66</td>
<td>0.66</td>
<td>0.65</td>
</tr>
<tr>
<td>US-NE2 (soybean, irrigated)</td>
<td>0.42</td>
<td>0.31</td>
<td>0.43</td>
<td>0.40</td>
<td>0.42</td>
</tr>
<tr>
<td>US-NE3 (corn, rainfed)</td>
<td>0.71</td>
<td>0.45</td>
<td>0.73</td>
<td>0.67</td>
<td>0.72</td>
</tr>
<tr>
<td>US-NE3 (soybean, rainfed)</td>
<td>0.43</td>
<td>0.28</td>
<td>0.44</td>
<td>0.39</td>
<td>0.44</td>
</tr>
</tbody>
</table>
Table 3. Coefficients of determination ($R^2$), root mean square errors (RMSE, g C m$^{-2}$ d$^{-1}$) and coefficients of variation (CV) for simulated GPP with the VIs using two options: original unscaled VIs versus scaled VIs, compared to tower daily GPP.

<table>
<thead>
<tr>
<th></th>
<th>NDVI</th>
<th>EVI</th>
<th>WDRVI$_{\text{green}}$</th>
<th>Cl$_{\text{green}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>original</td>
<td>scaled</td>
<td>original</td>
<td>scaled</td>
</tr>
<tr>
<td>US-NE1</td>
<td>$R^2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.67</td>
<td>0.80</td>
<td>0.8</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td>RMSE</td>
<td>4.85</td>
<td>3.77</td>
<td>3.74</td>
</tr>
<tr>
<td></td>
<td>CV</td>
<td>31%</td>
<td>24%</td>
<td>24%</td>
</tr>
<tr>
<td>US-NE2</td>
<td>$R^2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(corn)</td>
<td>0.72</td>
<td>0.81</td>
<td>0.83</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td>RMSE</td>
<td>4.38</td>
<td>3.62</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>CV</td>
<td>26%</td>
<td>22%</td>
<td>21%</td>
</tr>
<tr>
<td>US-NE2</td>
<td>$R^2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(soybean)</td>
<td>0.63</td>
<td>0.78</td>
<td>0.75</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>RMSE</td>
<td>3.16</td>
<td>2.45</td>
<td>2.61</td>
</tr>
<tr>
<td></td>
<td>CV</td>
<td>31%</td>
<td>24%</td>
<td>26%</td>
</tr>
<tr>
<td>US-NE3</td>
<td>$R^2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(corn)</td>
<td>0.63</td>
<td>0.80</td>
<td>0.7</td>
<td>0.81</td>
</tr>
<tr>
<td></td>
<td>RMSE</td>
<td>4.66</td>
<td>3.44</td>
<td>4.14</td>
</tr>
<tr>
<td></td>
<td>CV</td>
<td>33%</td>
<td>25%</td>
<td>30%</td>
</tr>
<tr>
<td>US-NE3</td>
<td>$R^2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(soybean)</td>
<td>0.5</td>
<td>0.75</td>
<td>0.63</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td>RMSE</td>
<td>3.35</td>
<td>2.38</td>
<td>2.88</td>
</tr>
<tr>
<td></td>
<td>CV</td>
<td>36%</td>
<td>26%</td>
<td>31%</td>
</tr>
</tbody>
</table>