New developments in the remote estimation of the fraction of absorbed photosynthetically active radiation in crops

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[1] The fraction of absorbed photosynthetically active radiation, *f*APAR, is an important biophysical characteristic in models of gas exchange between the terrestrial boundary layer and the atmosphere, as well as in the analysis of vegetation productivity. Synoptic estimation of *f*APAR has been performed by using NDVI as a linear proxy of *f*APAR, despite the saturation of NDVI at *f*APAR beyond 0.7. This paper analyzes the NDVI/*f*APAR relationship in row crops (i.e. maize and soybean), and evaluates alternative vegetation indices to overcome the loss of sensitivity of NDVI at moderate-to-high vegetation biomass. Red-edge NDVI, which uses NIR and a band around 700 nm and the recently proposed Wide Dynamic Range Vegetation Index, which uses red and NIR bands only, were found to be sensitive to *f*APAR variation along its entire range and exhibited significant increase in sensitivity to *f*APAR. **Citation:** Viña, A., and A. A. Gitelson (2005), New developments in the remote estimation of the fraction of absorbed photosynthetically active radiation in crops, *Geophys. Res. Lett.*, *32*, L17403, doi:10.1029/2005GL023647.

1. Introduction

[2] Terrestrial vegetation constitutes a major, if not dominant, element of the interface between the land surface and the atmosphere. Quantifying the biophysical properties of terrestrial vegetation and their variation through time is important for a rapid and accurate assessment of the status of the vegetation and its responses to changing environmental conditions. One of such biophysical characteristics is the fraction of absorbed photosynthetically active radiation (*f*APAR). It is one of the main players used in the formulation of production efficiency models (PEM). Numerous studies [e.g., *Asrar et al.*, 1992; *Sellers*, 1985] found that under specified canopy reflectance properties, *f*APAR can be estimated remotely, using the Normalized Difference Vegetation Index (NDVI = $(R_{NIR} - R_{red})/(R_{NIR} + R_{red})$, where R_{NIR} and R_{red} are reflectances in the near-infrared (NIR) and the red spectral regions, respectively). Several PEMs have been developed that use synoptic NDVI data to estimate net primary production [e.g., *Running et al.*, 2004]. Nevertheless, *Ruimy et al.* [1994] underscored the fact that the linear relationship between *f*APAR and NDVI is an approximation, and it is only valid during the growing stage. A likely explanation for this is that during the reproductive and senescence stages in crops, the canopy still intercepts the incoming radiation, but the leaves contain less photosynthetic pigments, which leads to a decrease in the NDVI [*Hatfield et al.*, 1984; *Gallo et al.*, 1985]. Therefore, since only the green components of the canopy are used for photosynthesis, *f*APAR needs to be separated into its photosynthetically and non-photosynthetically active components, in order to improve the estimation of vegetation productivity over time [e.g., *Hall et al.*, 1992].

[3] A significant decrease in the sensitivity of NDVI has been observed when *f*APAR exceeds 0.7 [e.g., *Asrar et al.*, 1984; *Goward and Huemmerich*, 1992], concealing changes in vegetation with moderate-to-high biomass. In this paper, we evaluate the NDVI vs. *f*APAR relationship in maize and soybean grown under irrigated and rainfed conditions, and test other spectral vegetation indices in order to overcome the decreased sensitivity of NDVI to *f*APAR at moderate-to-high biomass densities. These indices were calculated using the discrete spectral bands of contemporary space-borne sensors: the green (545–565 nm) and NIR (840–870 nm) bands of the MODIS system (onboard NASA's Terra and Aqua satellite), and the red edge (703.75–713.75 nm) and NIR (750–757.5 nm) bands of the MERIS system (onboard the polar orbiting Envisat Earth Observation Satellite).

2. Methods

[4] The study took place during the growing seasons of 2001, 2002 and 2003 at a University of Nebraska-Lincoln research facility located 58 km northeast of Lincoln NE, U.S.A., and consists of three agricultural sites; the first two are 65-ha fields equipped with center pivot irrigation systems. The third site is of approximately the same size, but relies entirely on rainfall. Site 1 is under continuous maize, while sites 2 and 3 are under maize-soybean rotation. Soils of the study area are deep silty clay loam [*Suyker et al.*, 2004].

[5] Daily 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] and

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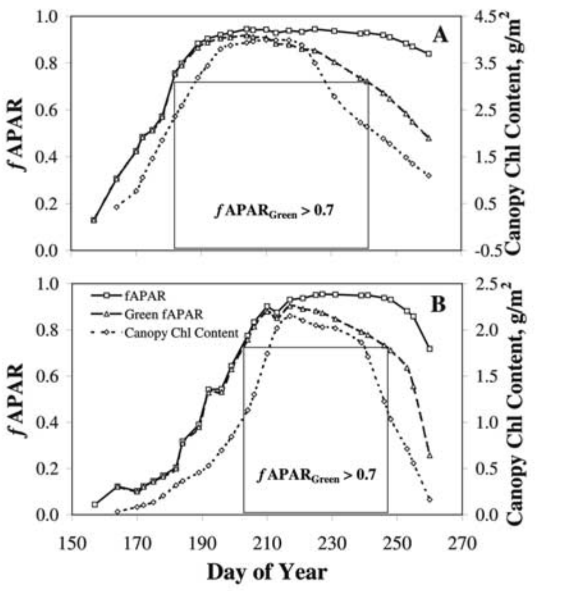

Figure 1. Temporal progression of fAPAR, $f\text{APAR}_{\text{Green}}$, and chlorophyll content in irrigated maize (a) and soybean (b).

Burba [2005]). Absorbed PAR (APAR) was calculated as [*Goward and Huemmerich*, 1992]:

$$\text{APAR} = \text{PAR}_{\text{inc}} - \text{PAR}_{\text{out}} - \text{PAR}_{\text{transm}} + \text{PAR}_{\text{soil}} \qquad (1)$$

fAPAR was calculated as $\text{APAR}/\text{PAR}_{\text{inc}}$.

[6] Spectral reflectance measurements of upper canopy leaves were collected biweekly during the growing seasons in the range 400 to 900 nm using a leaf clip with bifurcated fiber-optic attached to both an Ocean Optics USB2000 spectroradiometer and to an Ocean Optics LS-1 light source (details by *Gitelson et al.* [2005]). Chl of each top leaf, $\text{Chl}_{\text{upper}}$, was then retrieved from reflectance applying a non-destructive technique [*Gitelson et al.*, 2003a]. Total Chl in the canopy was estimated as $\text{Chl}_{\text{est}} = \text{Chl}_{\text{upper}}$*Green LAI. Green LAI was measured destructively (details by *Gitelson et al.* [2003b]).

[7] Reflectance measurements at canopy level were carried out from June until October in 2001 growing season (18 measurement campaigns), and from May until October in 2002 and 2003 (31 and 34 measurement campaigns in 2002 and 2003, respectively). A dual-fiber system, with two inter-calibrated Ocean Optics USB2000 radiometers, mounted on an all-terrain sensor platform [*Rundquist et al.*, 2004] was used to collect canopy reflectance data in the range 400–900 nm with a sampling interval of 0.3 nm and a spectral resolution of around 1.5 nm (details by *Viña et al.* [2004a]).

[8] To estimate how sensitive is each of the vegetation indices evaluated in this paper, to changes in fAPAR, the noise equivalent fAPAR (NE ΔfAPAR) was calculated [*Govaerts et al.*, 1999]:

$$\text{NE } \Delta f\text{APAR} = \text{RMSE}/[\text{d(VI)}/\text{d}(f\text{APAR})] \qquad (2)$$

Where RMSE is Root Mean Square Error of the relationship between vegetation index (VI) and fAPAR. Noise equivalent defined in this way allows the direct comparison among different indices, with different scales and dynamic ranges.

3. Results and Discussion

[9] Aboveground crop biomass tends to follow a well-defined temporal pattern, indicating a cumulative increase in the amount of energy absorbed by the developing canopy during the growing season (Figure 1). fAPAR shows a progressive increase during the vegetative stage until maximum canopy development, and then remains virtually invariant during the reproductive stage, with a decrease during the senescence stage. In soybean (Figure 1b) this decrease is particularly conspicuous due to a drastic loss of leaf cover. The increase in fAPAR coincided with an increase in canopy Chl content during the vegetative stage, up to a point in which further increases in canopy Chl almost did not induce increases in fAPAR (corresponding to Green LAI > 2). In contrast, during the reproductive and senescence stages (Day of the year, DOY, beyond 190 in maize and 215 in soybean) fAPAR remained almost insensitive to decreases in canopy Chl. During these stages, the crops absorb PAR due to photosynthetic and non-photosynthetic components, but the contribution of the photosynthetic component decreases considerably toward the end of the season. Therefore, although the canopy is still intercepting PAR, it is progressively less used for photosynthesis. To obtain a measure of the fAPAR absorbed only by the photosynthetic component of the vegetation, we calculated $f\text{APAR}_{\text{green}} = f\text{APAR} \times$ (green LAI/total LAI) [see *Hall et al.*, 1992; *Hanan et al.*, 2002].

[10] Figures 2a and 2b show the relationships NDVI vs. fAPAR and $f\text{APAR}_{\text{green}}$ for crops. Since NDVI exhibits sensitivity to changes in canopy Chl, the NDVI/fAPAR relationship shows hysteresis, due to the fact that during the

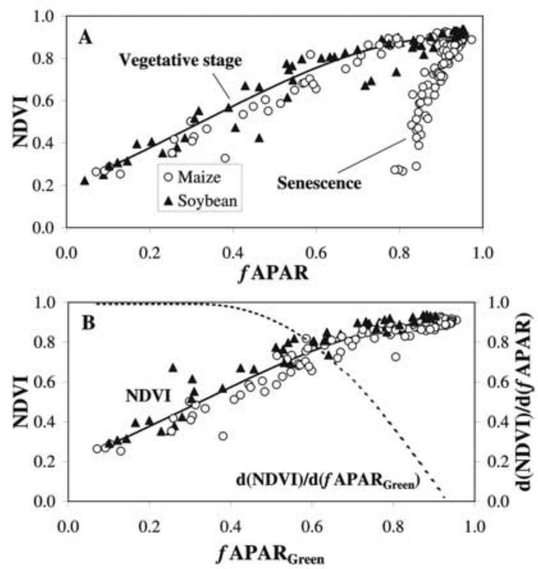

Figure 2. Relationship NDVI vs. fAPAR (a) and NDVI vs. $f\text{APAR}_{\text{green}}$ (b) for irrigated and rainfed maize and soybean. Dotted line in (b) is the first derivative of the best fit polynomial function of NDVI vs. $f\text{APAR}_{\text{Green}}$ with respect to $f\text{APAR}_{\text{green}}$.

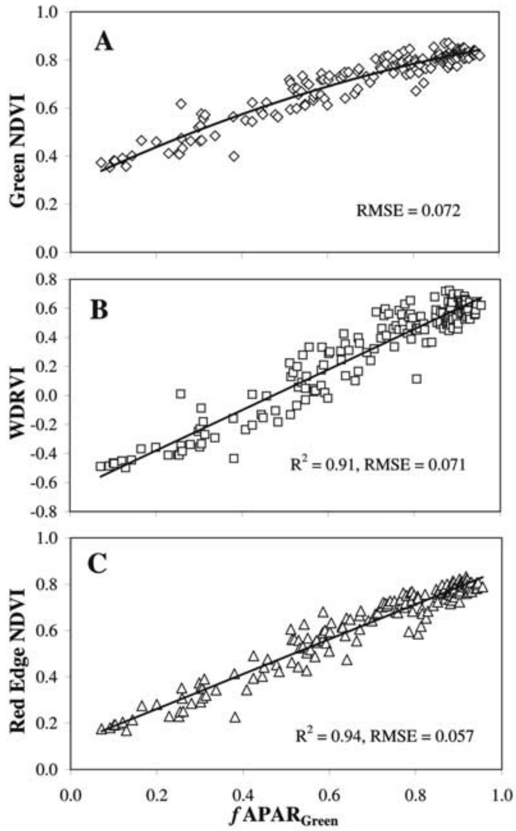

Figure 3. Relationship between (a) Green NDVI (polynomial function), (b) WDRVI with α = 0.2 (linear function) and (c) Red-edge NDVI vs. $f\mathrm{APAR}_{\mathrm{Green}}$ (linear function) for maize and soybean. All regression lines are significant at the 0.01 level.

reproductive stage and at the beginning of senescence the *f*APAR remains almost insensitive to reductions in Chl (especially in maize), while the NDVI exhibits a considerable reduction (Figure 2a). In addition, during the vegetative stage, NDVI/*f*APAR relationship is almost non-species specific but it becomes species specific during senescence: the same decrease in NDVI corresponds to a significant drop in *f*APAR of soybean and only a slight decrease in maize.

[11] Although *f*APAR is insensitive to changes in chlorophyll content at the reproductive and senescence stages (as suggested by Figure 1 and by *Dawson et al.* [2003]), the green portion of *f*APAR, the photosynthetic component, is sensitive to chlorophyll content. The NDVI/$f\mathrm{APAR}_{\mathrm{green}}$ relationship shows no hysteresis and is not significantly different for both species (Figure 2b). Thus, NDVI can be thought of as a proxy of green *f*APAR, although an asymptotic relationship is observed, with a significant decrease in the slope as *f*APAR exceeds 0.5, as has been observed by several authors [e.g. *Kanemasu*, 1974; *Baret and Guyot*, 1991; *Myneni et al.*, 1997]. Thus, NDVI exhibits limitations at moderate-to-high vegetation density: its sensitivity to $f\mathrm{APAR}_{\mathrm{green}}$ drops twofold for $f\mathrm{APAR}_{\mathrm{green}}$ = 0.74 and tenfold for $f\mathrm{APAR}_{\mathrm{green}}$ = 0.89. This limitation is due to: 1) choices of band location and width [e.g., *Sellers*, 1985; *Yoder and Waring*, 1994; *Gitelson et al.*, 1996]; and 2) the very mathematical formulation of the NDVI: the normalization procedure makes the NDVI insensitive to variation in R_{NIR} when $R_{\mathrm{NIR}} \gg R_{\mathrm{red}}$ [*Gitelson*, 2004]. It prevents accurate estimation of $f\mathrm{APAR}_{\mathrm{green}} > 0.7$, which corresponds to more than two months of the growing season in the crops studied (Figure 1).

[12] To correct for this significant loss of sensitivity, different spectral bands have been incorporated into the mathematical formulation of NDVI, as well as new indices have been developed. A Red edge NDVI [*Gitelson and Merzlyak*, 1994] and a Green NDVI [*Gitelson et al.*, 1996] use the same NDVI formulation, but with the red edge (around 700 nm) and the green (around 550 nm) bands, respectively. More recently, the Wide Dynamic Range Vegetation Index (WDRVI) was developed [*Gitelson*, 2004]. WDRVI is a non-linear function of NDVI, thus, it can be obtained from NDVI by:

$$\mathrm{WDRVI} = [(\alpha + 1)\mathrm{NDVI} + (\alpha - 1)]/[(\alpha - 1)\mathrm{NDVI} + (\alpha + 1)] \tag{3}$$

The weighting coefficient α is introduced to attenuate the contribution of the NIR region at moderate-to-high green biomass, and to make it comparable to that of the red region. The specific magnitude of this coefficient depends primarily on sensor characteristics and observational conditions [*Gitelson*, 2004; *Viña et al.*, 2004b].

[13] Green NDVI exhibited more sensitivity to moderate-to-high $f\mathrm{APAR}_{\mathrm{green}}$ than that of NDVI; however, the sensitivity decreases as $f\mathrm{APAR}_{\mathrm{green}}$ exceeded 0.8. Both WDRVI (with α = 0.2) and the Red edge NDVI were linearly related to $f\mathrm{APAR}_{\mathrm{green}}$ with coefficients of determination of 0.91 and 0.94, respectively (Figure 3).

[14] Noise equivalent of Green NDVI and Red edge NDVI were similar, but higher than that of NDVI, for $f\mathrm{APAR}_{\mathrm{green}} < 0.4$ (Figure 4). In this range of $f\mathrm{APAR}_{\mathrm{green}}$, the noise equivalent of WDRVI was higher than that of the other indices, and the noise equivalent of NDVI was the lowest (Figure 4). As $f\mathrm{APAR}_{\mathrm{green}} > 0.4$, noise equivalent of both NDVI and Green NDVI increased, however, noise equivalent of Green NDVI remained below that of NDVI. When $f\mathrm{APAR}_{\mathrm{green}} > 0.6$, the noise equivalent of Red edge NDVI and WDRVI are lower than that of both NDVI and Green NDVI, with noise equivalent of Red edge NDVI being the lowest of all indices (Figure 4).

4. Conclusions

[15] To obtain accurate synoptic estimates of $f\mathrm{APAR}_{\mathrm{green}}$ at moderate-to-high vegetation biomass densities, where

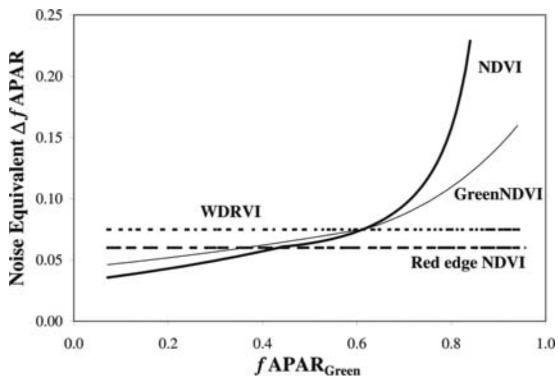

Figure 4. Noise equivalent $\Delta f\mathrm{APAR}_{\mathrm{Green}}$ for all indices evaluated.

NDVI loses sensitivity, alternative indices can be used. The choice of the alternative index depends on the spectral characteristics of the sensor system at hand. Red-edge NDVI appears to be the best index for such estimation. Thus, it can be used in satellite systems with spectral bands in the red edge region (e.g., ESA's MERIS, NASA's Hyperion).

[16] The WDRVI exhibited high sensitivity to $f\mathrm{APAR}_{green}$ at its entire range of variation. It can be employed to estimate $f\mathrm{APAR}_{green}$ using such sensors as MODIS, Landsat and AVHRR, among others. The differential sensitivity of the NDVI and the WDRVI to $f\mathrm{APAR}_{green}$ could be combined. A smooth weighting function that selects the NDVI for $f\mathrm{APAR}_{green} < 0.6$ and the WDRVI for $f\mathrm{APAR}_{green} > 0.6$ could optimize monitoring of $f\mathrm{APAR}_{green}$ using a single, blended index [details by *Gitelson and Kaufman*, 1998].

[17] The implications of these findings are far-reaching. Diverse regional to global studies requiring synoptic data on terrestrial vegetation will benefit from the increased accuracy of fAPAR_{green} estimation through the WDRVI, the Red edge NDVI, and the Green NDVI.

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References

Asrar, G., M. Fuchs, E. T. Kanemasu, and J. H. Hatfield (1984), Estimating absorbed photosynthetic radiation and leaf area index from spectral reflectance in wheat, *Agron J.*, *76*, 300–306.

Baret, F., and G. Guyot (1991), Potentials and limits of vegetation indices for LAI and APAR assessment, *Remote Sens. Environ.*, *35*, 161–173.

Burba, G. (2005), Water and energy fluxes in native tallgrass prairie and cultivated wheat ecosystems, Ph.D. diss., 87 pp., Univ. of Nebraska-Lincoln, Lincoln.

Dawson, T. P., P. R. J. North, S. E. Plummer, and P. J. Curran (2003), Forest ecosystem chlorophyll content: Implications for remotely sensed estimates of net primary productivity, *Int. J. Remote Sens.*, *24*, 611–617.

Gallo, K. P., C. S. T. Daughtry, and M. E. Bauer (1985), Spectral estimation on absorbed photosynthetically active radiation in corn canopies, *Remote Sens. Environ.*, *17*, 221–232.

Gitelson, A. A. (2004), Wide Dynamic Range Vegetation Index for remote quantification of biophysical characteristics of vegetation, *J. Plant Physiol.*, *161*, 165–173.

Gitelson, A., and Y. Kaufman (1998), MODIS NDVI optimization to fit the AVHRR data series—Spectral considerations, *Remote Sens. Environ.*, *66*, 343–350.

Gitelson, A. A., and M. Merzlyak (1994), Spectral reflectance changes associated with autumn senescence of Asculus hippocastanum and Acer platanoides leaves: Spectral features and relation to chlorophyll estimation, *J. Plant Physiol.*, *143*, 286–292.

Gitelson, A. A., Y. Kaufman, and M. N. Merzlyak (1996), Use of green channel in remote sensing of global vegetation from EOS-MODIS, *Remote Sens. Environ.*, *58*, 289–298.

Gitelson, A. A., U. Gritz, and M. N. Merzlyak (2003a), Relationships between leaf chlorophyll content and spectral reflectance and algorithms for non-destructive chlorophyll assessment in higher plant leaves, *J. Plant Physiol.*, *160*, 271–282.

Gitelson, A. A., A. Viña, T. J. Arkebauer, D. C. Rundquist, G. Keydan, and B. Leavitt (2003b), Remote estimation of leaf area index and green leaf biomass in maize canopies, *Geophys. Res. Lett.*, *30*(5), 1248, doi:10.1029/2002GL016450.

Gitelson, A. A., A. Viña, V. Ciganda, D. C. Rundquist, and T. J. Arkebauer (2005), Remote estimation of canopy chlorophyll content in crops, *Geophys. Res. Lett.*, *32*, L08403, doi:10.1029/2005GL022688.

Govaerts, Y. M., M. M. Verstraete, B. Pinty, and N. Gobron (1999), Designing optimal spectral indices: A feasibility and proof of concept study, *Int. J. Remote Sens.*, *20*, 1853–1873.

Goward, S. M., and K. E. Huemmerich (1992), Vegetation canopy PAR absorptance and the Normalized Difference Vegetation Index: An assessment using SAIL model, *Remote Sens. Environ.*, *39*, 119–140.

Hall, F. G., K. F. Huemmrich, S. J. Goetz, P. J. Sellers, and J. E. Nickeson (1992), Satellite remote sensing of surface energy balance: Success, failures and unresolved issues in FIFE, *J. Geophys. Res.*, *97*, 19,061–19,089.

Hanan, N. P., G. Burba, S. B. Verma, J. A. Berry, A. Suyker, and E. A. Walter-Shea (2002), Inversion of net ecosystem CO_2 flux measurements for estimation of canopy PAR absorption, *Global Change Biol.*, *8*, 563–574.

Hatfield, J. L., G. Asrar, and E. T. Kanemasu (1984), Intercepted photosynthetically active radiation estimated by spectral reflectance, *Remote Sens. Environ.*, *14*, 65–75.

Kanemasu, E. T. (1974), Seasonal canopy reflectance patterns of wheat, sorghum and soybean, *Remote Sens. Environ.*, *3*, 43–47.

Myneni, R. B., R. R. Nemani, and S. W. Running (1997), Estimation of global leaf area index and absorbed PAR using radiative transfer models, *IEEE Trans. Geosci. Remote Sens.*, *35*, 1380–1393.

Ruimy, A., B. Saugier, and G. Dedieu (1994), Methodology for the estimation of terrestrial net primary production from remotely sensed data, *J. Geophys. Res.*, *99*, 5263–5283.

Rundquist, D. C., R. Perk, B. Leavitt, G. P. Keydan, and A. A. Gitelson (2004), Collecting spectral data over cropland vegetation using machine-positioning versus hand-positioning of the sensor, *Comput. Electr. Agric.*, *43*, 173–178.

Running, S. W., R. R. Nemani, F. A. Heinsch, M. Zhao, M. Reeves, and H. Hashimoto (2004), A continuous satellite-derived measure of global terrestrial primary production, *BioScience*, *54*, 547–560.

Sellers, P. J. (1985), Canopy reflectance, photosynthesis and transpiration, *Int. J. Remote Sens.*, *6*, 1335–1372.

Suyker, A. E., S. B. Verma, G. G. Burba, T. J. Arkebauer, D. T. Walters, and K. G. Hubbard (2004), Growing season carbon dioxide exchange in irrigated and rainfed maize, *Agric. For. Meteorol.*, *124*, 1–13.

Viña, A., A. A. Gitelson, D. C. Rundquist, G. Keydan, B. Leavitt, and J. Schepers (2004a), Monitoring maize (*Zea mays* L.) phenology with remote sensing, *Agric. J.*, *96*, 1139–1147.

Viña, A., G. M. Henebry, and A. A. Gitelson (2004b), Satellite monitoring of vegetation dynamics: Sensitivity enhancement by the Wide Dynamic Range Vegetation Index, *Geophys. Res. Lett.*, *31*(4), L04503, doi:10.1029/2003GL019034.

Yoder, B. J., and R. H. Waring (1994), The Normalized Difference Vegetation Index of small Douglas-Fir canopies with varying chlorophyll concentrations, *Remote Sens. Environ.*, *48*, 81–91.

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