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Gitelson, Anatoly A.; Verma, Shashi B.; Viña, Andrés; Rundquist, Donald C.; Keydan, Galina P.; Leavitt, Bryan; Arkebauer, Timothy J.; Burba, George G.; and Suyker, Andrew E., "Novel technique for remote estimation of CO_2 flux in maize" (2003). *Papers in Natural Resources*. 275.
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Novel technique for remote estimation of CO_2 flux in maize

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Received 30 October 2002; revised 8 January 2003; accepted 24 January 2003; published 13 May 2003.

[1] There is considerable interest in assessing the magnitude of carbon sources and sinks for agricultural lands, grasslands, and forests. In this paper, we propose a novel technique to remotely assess CO_2 fluxes in maize using reflectances (ρ) in two spectral channels either in the green around 550 nm or in the red edge near 700 nm and the NIR (beyond 750 nm). Differences of reciprocal reflectances $[(\rho_{Green})^{-1} - (\rho_{NIR})^{-1}]$ and $[(\rho_{RedEdge})^{-1} - (\rho_{NIR})^{-1}]$ accounted for more than 90 percent of the variability in mid-day canopy photosynthesis of irrigated maize. The technique was validated by an independent data set; root mean square error in predicting mid-day canopy photosynthesis by $[(\rho_{RedEdge})^{-1} - (\rho_{NIR})^{-1}]$ was 0.17 mg/m^2/s and 0.2 mg/m^2/s by $[(\rho_{Green})^{-1} - (\rho_{NIR})^{-1}]$. *INDEX TERMS:* 1640 Global Change: Remote sensing; 1615 Global Change: Biogeochemical processes (4805); 1694 Global Change: Instruments and techniques. **Citation:** Gitelson, A. A., S. B. Verma, A. Viña, D. C. Rundquist, G. Keydan, B. Leavitt, T. J. Arkebauer, G. G. Burba, and A. E. Suyker, Novel technique for remote estimation of CO_2 flux in maize, *Geophys. Res. Lett.*, *30*(9), 1486, doi:10.1029/2002GL016543, 2003.

1. Introduction

[2] The daily rate of carbon accumulation is the product of absorbed photosynthetically active radiation (aPAR) and the radiation use efficiency, RUE [*Monteith*, 1972]. The Simple Ratio and the Normalized Difference Vegetation Index (NDVI) have been most frequently used to estimate biophysical parameters of vegetation [e.g., *Tucker et al.*, 1981; *Asrar et al.*, 1984; *Sellers*, 1987; *Myneni et al.*, 1992]. The theoretical analysis by *Sellers* [1987], supported empirically by *Verma et al.* [1993] showed that the Simple Ratio should be near-linearly related to the derivatives of canopy photosynthesis with respect to PAR. *Peñuelas et al.* [1995] proposed the photochemical reflectance index (PRI), based on narrow spectral bands at 531 and 570 nm. PRI was related with some success to RUE of several plant species, thus enabling the estimation of stand photosynthesis from remotely sensed data. However, *Barton and North* [2001] showed that PRI is most sensitive to changes in leaf area index (LAI), and concluded that the potential use of the index to predict canopy RUE will require an independent estimate of changes in LAI.

[3] In this paper, we use reciprocal reflectance in the green and red edge spectral regions for quantitative remote estimation of net CO_2 uptake in irrigated maize. We will demonstrate the advantage of this technique for estimating mid-day CO_2 fluxes over the traditional approaches, which use NDVI-like indices.

2. Methods

[4] A pilot study was conducted in 2001 to examine the relationship between remotely measured reflectance and CO_2 fluxes for a maize canopy. The project was carried out in two irrigated production fields (each 65 ha) with sufficient upwind fetch of uniform vegetation cover required for adequately measuring landscape-level fluxes of CO_2, water vapor and energy using the micrometeorological eddy covariance technique [cf. *Verma*, 1990; *Suyker and Verma*, 2001]. Soil-surface CO_2 exchanges were measured using portable gas exchange equipment. Canopy photosynthesis (P_c) was calculated as the sum of the fluxes measured by the eddy covariance sensors and the soil fluxes.

[5] Spectral measurements were made using a dual-fiber system with two inter-calibrated Ocean Optics USB2000 radiometers mounted on an all-terrain sensor platform [*Rundquist et al.*, 2001]. The data were collected in the range 400–900 nm with a spectral resolution of about 1.5 nm. Radiometer #1, equipped with a 25° field-of-view optical fiber was pointed downward to measure the upwelling radiance of maize (L_λ^{maize}). The position of the radiometer above the canopy was kept constant along the growing season (i.e. around 5.4 m), yielding a sampling area with a diameter of around 2.4 m. Radiometer #2, equipped with an optical fiber and cosine diffuser (yielding a hemispherical field of view), was pointed upward to simultaneously measure incident irradiance (E_λ^{inc}). To match their transfer functions, the inter-calibration of the radiometers was accomplished by measuring the upwelling radiance (L_λ^{cal}) of a white Spectralon (Labshere, Inc., North Sutton, NH) reflectance standard, simultaneously with incident irradiance (E_λ^{cal}). To mitigate the impact of solar elevation on radiometer intercalibration, the anisotropic reflectance from the calibration target was corrected in accord with *Jackson et al.* [1992]. Percent reflectance, ρ_λ, was computed as:

$$\rho_\lambda = \left(L_\lambda^{maize}/L_\lambda^{cal}\right)*\left(E_\lambda^{cal}/E_\lambda^{inc}\right)*100*\rho_\lambda^{cal} \quad (1)$$

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Table 1. Average Digital Numbers in Two HYPERION Images (band 35, around 700 nm) of 30 Randomly Selected Pixels Within the Whole Sites and Within the Areas Sampled by Sensors on the "Goliath", an All-Terrain Platform, Respectively

	Date	Goliath Sample Area	Entire Field	T-test	P-value
Site 1	**8/13/01**	826.83 (17.19)	820.64 (17.62)	0.94	0.35
	8/29/01	808.85 (10.59)	807.69 (11.81)	0.27	0.79
Site 2	**8/13/01**	840.79 (16.34)	842.79 (38.58)	−0.22[a]	0.83
	8/29/01	835.01 (15.95)	825.24 (23.81)	1.19	0.24

Numbers in parentheses correspond to standard deviations. T-test values and P-values correspond to the comparison of means of sampled areas and the entire field.

[a]Two sample T-test assuming unequal variances.

where ρ_λ^{cal} is the reflectance of the Spectralon panel linearly interpolated to match the band centers of each radiometer.

[6] The use of two inter-calibrated hyperspectral radiometers allows simultaneous measurement of downwelling irradiance and upwelling target radiance. The dual-fiber approach results in fast measurement and minimal error due to variation in irradiation condition. One critical issue with regard to the dual-fiber approach is that the transfer functions of both radiometers must be identical. We tested our Ocean Optics instruments under laboratory conditions; over a four-hour period the standard deviations of the ratio of the two transfer functions did not exceed 0.004.

[7] Radiometric data were collected close to solar noon (between 11:00 and 13:00); during this period, changes in solar zenith angle were minimal. On each measurement date, six randomly selected plots were established per field, each with six randomly selected sampling points. Measurements took about 5 minutes per plot and about 30 minutes per field. The two radiometers were inter-calibrated immediately before and immediately after measurement in each field. Eighteen campaigns were carried out from the beginning of June to the beginning of October, 2001.

[8] Field heterogeneity was tested using two HYPERION images acquired in August 13 and 29, 2001. HYPERION is a hyperspectral imager with a spatial resolution of 30 m/pixel onboard NASA's Earth Observing-1 satellite. The average digital numbers of band 35 (around 700 nm) of the entire fields were compared against the average digital numbers within the areas sampled from the "Goliath" platform and no statistically significant differences were obtained (Table 1). Thus, test sites where reflectance measurements were conducted were representative of the entire field.

3. Results and Discussion

[9] Net CO_2 uptake or canopy photosynthesis, P_c, showed two types of variations (Figure 1). The first one related mainly to the phenological changes of the canopy (e.g., changes in vegetation fraction, LAI, and pigment content among others). The other type of P_c variation had much higher frequency. It was linked to the variations in the incoming PAR. P_c was small early in the growing season and reached maximal values by the middle of July (DOY 198). From the end of July, P_c continuously decreased from ~2 to ~0.3 mg/m^2/s at the end of September (DOY 270).

[10] NDVI responded to the status of vegetation early in growing season (Figure 2a), but then leveled off. When P_c exceeded 1.0 mg/m^2/s, the slope of the relationship NDVI vs. P_c diminished progressively, becoming less than 0.05 (mg/m^2/s)$^{-1}$ and NDVI was virtually invariant with respect to P_c (Figure 2b). Other indices used for estimation of vegetation status (e.g., SAVI, ARVI, and GARI) also showed low sensitivity to fluxes exceeding 1.0 mg/m^2/s (data not shown).

[11] In the range of leaf reflectance, ρ_λ, from 0 to 50%, reciprocal reflectance, $(\rho_\lambda)^{-1}$, is closely related to the ratio

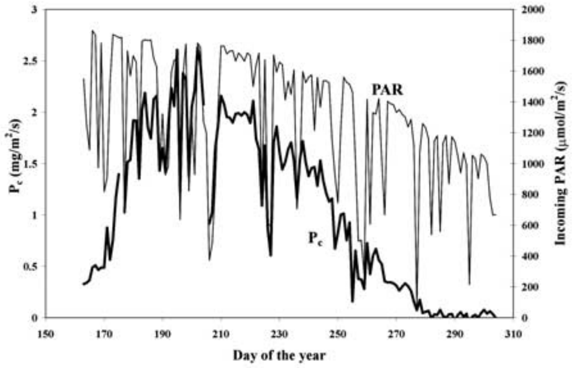

Figure 1. Temporal behavior of mid-day (11:00–13:00 hours) values of canopy photosynthesis (P_c) of maize and incident photosynthetic active radiation (PAR), during the growing season of 2001.

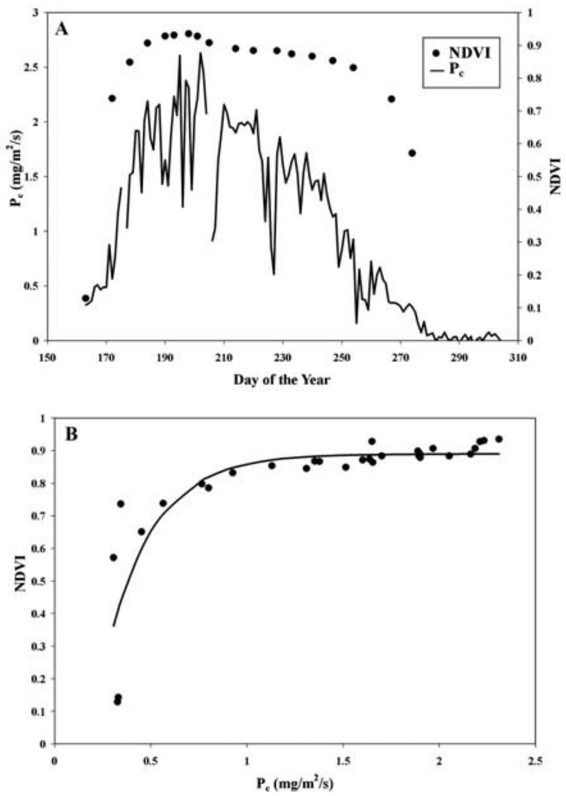

Figure 2. (A) Temporal behavior of NDVI and mid-day canopy photosynthesis (P_c) of maize, during the growing season of 2001. (B) Relationship between NDVI and mid-day canopy photosynthesis (P_c), established for both study sites.

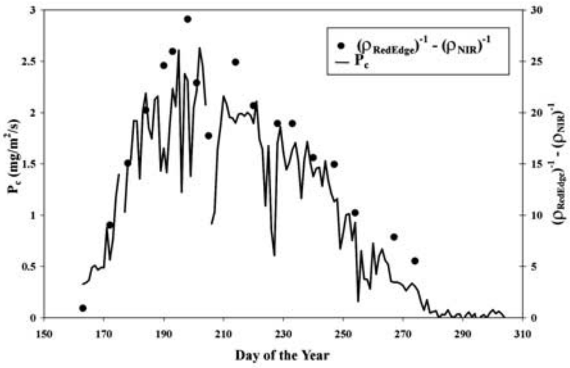

Figure 3. Temporal behavior of the index $[(\rho_{RedEdge})^{-1} - (\rho_{NIR})^{-1}]$ and mid-day canopy photosynthesis (P_c) of maize during the growing season of 2001. The index $[(\rho_{Green})^{-1} - (\rho_{NIR})^{-1}]$ had very similar temporal behavior.

of absorption coefficient to scattering coefficient [*Gitelson et al.*, 2003]. Reciprocal reflectance of leaves in the green (around 550 nm) and red edge (around 700 nm) ranges, $(\rho_{Green})^{-1}$ and $(\rho_{RedEdge})^{-1}$, were found to be closely linearly related to total pigment content [*Gitelson et al.*, 2001, 2002]. It was shown recently that subtraction involving reciprocal reflectance in the NIR range, $(\rho_{NIR})^{-1}$, from $(\rho_{RedEdge})^{-1}$ and $(\rho_{Green})^{-1}$ made the indices $[(\rho_{RedEdge})^{-1} - (\rho_{NIR})^{-1}]$ and $[(\rho_{Green})^{-1} - (\rho_{NIR})^{-1}]$ linearly proportional to leaf chlorophyll content [*Gitelson et al.*, 2003]. We hypothesized that at landscape level $[(\rho_{RedEdge})^{-1} - (\rho_{NIR})^{-1}]$ and $[(\rho_{Green})^{-1} - (\rho_{NIR})^{-1}]$ will be related to total chlorophyll content in vegetation and, as a result, related to net uptake of CO_2 (or canopy photosynthesis).

[12] As we hypothesized, the indices $[(\rho_{RedEdge})^{-1} - (\rho_{NIR})^{-1}]$ and $[(\rho_{Green})^{-1} - (\rho_{NIR})^{-1}]$ responded to phenological variations in the status of maize, as it changed with the progression of the growing season (Figure 3). With an increase in LAI the indices increased reaching maximal values at DOY 198. When tassels appeared on the maize plants, reflectances ρ_{Green} and $\rho_{RedEdge}$ increased, so the indices decreased, following canopy photosynthesis. From the end of July till the end of September indices continuously decreased.

[13] Canopy reflectance depends not only on vegetation conditions but also on atmospheric conditions. When a cloud obscures the sun, the proportion of incoming diffuse radiation increases relative to the incoming direct component; both the spectral quality and the angular distribution of the incoming radiation are affected. Canopy radiance is altered due to its angular anisotropy and, more importantly, because of the partial or complete removal of shadows formed by vegetation [e.g., *Colwell*, 1974]. For a partially vegetated surface, comprising 40% vegetation, 20% shadowed soil and 40% sunlit soil, removing the shadow component causes an increase in reflectance of 5% in the NIR and at least 22% in the red part of the spectrum [*Milton*, 1981]. The same effect takes place for a closed canopy (100% vegetation fraction and the soil contribution to reflectance is insignificant). Following *Milton* [1981], we calculated the radiance of the vegetative area shadowed by a single leaf layer as the sum of the: (i) incoming radiation remaining after "filtering" by transmission through the leaf layer and then being reflected by other leaf surfaces to the sensor overhead, and (ii) diffuse skylight, which accounted for about 20% of total irradiation in the red part of the spectrum as per *Milton* [1981], being reflected by the leaves.

[14] The results imply that under cloud cover the reflectance of the areas being shadowed increases significantly (factor 4 to 5) in the green and the red edge regions. As a result, removing a 10% shadow component causes an increase in canopy reflectance of approximately 5% in NIR and 8% in the green and the red edge; removing a 20% shadow component causes an increase in reflectance of 8% in NIR and 15% in green and red edge. This explains why the indices $[(\rho_{RedEdge})^{-1} - (\rho_{NIR})^{-1}]$ and $[(\rho_{Green})^{-1} - (\rho_{NIR})^{-1}]$ were higher in bright sun than under cloud cover (Figure 3), as it was the case of P_c.

[15] The relationships between P_c and the indices $[(\rho_{RedEdge})^{-1} - (\rho_{NIR})^{-1}]$ (Figure 4a) and $[(\rho_{Green})^{-1} - (\rho_{NIR})^{-1}]$ (not shown) were linear, explaining about 90% of the variation in canopy photosynthesis. Indices $[(\rho_{RedEdge})^{-1} - (\rho_{NIR})^{-1}]$ and $[(\rho_{Green})^{-1} - (\rho_{NIR})^{-1}]$ were closely related: the coefficient of determination of linear relatioship between them was $r^2 > 0.88$. The approach was validated by an independent data set comparing the predicted canopy photosynthesis with the measured one. Linear models $[(\rho_{RedEdge})^{-1} - (\rho_{NIR})^{-1}]$ vs. P_c and $[(\rho_{Green})^{-1} - (\rho_{NIR})^{-1}]$ vs. P_c developed for site 1 were inversed and canopy photosynthesis, P_c^{pred}, was calculated using reflectances measured in site 2. Then P_c^{pred} was compared to the

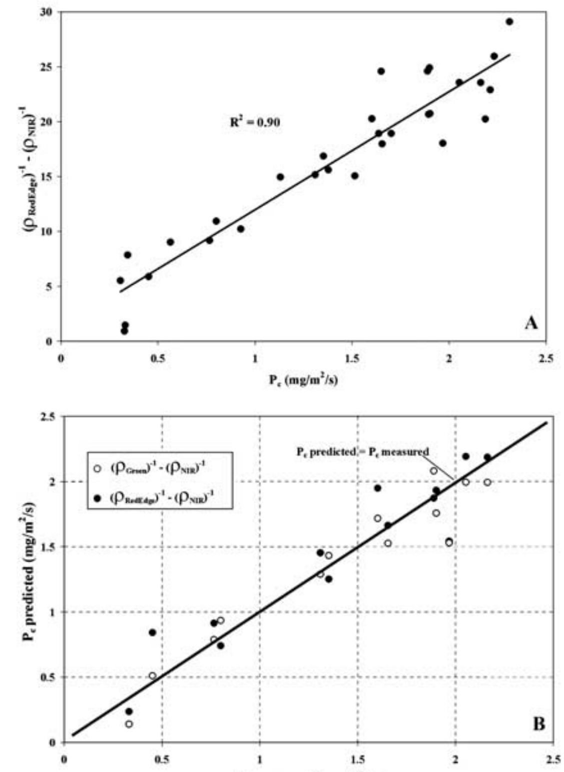

Figure 4. (A) Relationship between index $[(\rho_{RedEdge})^{-1} - (\rho_{NIR})^{-1}]$ and mid-day canopy photosynthesis (P_c). (B) Validation of the indices for canopy photosynthesis (P_c) prediction.

canopy photosynthesis measurements, P_c^{meas}, at site 2 (Figure 4b). The slope of best-fit function P_c^{pred} vs. P_c^{meas} was quite close to one ($P_c^{pred} = 0.9259 * P_c^{meas} + 0.0614$) and Root Mean Square Error of canopy photosynthesis prediction by the index $[(\rho_{Green})^{-1} - (\rho_{NIR})^{-1}]$ was 0.2 mg/m^2/s and it was 0.17 mg/m^2/s for the index $[(\rho_{RedEdge})^{-1} - (\rho_{NIR})^{-1}]$.

4. Conclusions

[16] Close relationships between remotely measured reflectance and mid-day canopy photosynthesis were found in a wide range of CO_2 flux (from near zero to 2.4 mg/m^2/s). Two spectral channels, either the green (around 550 nm) or red edge (near 700 nm) and near infrared (beyond 750 nm), are sufficient to estimate CO_2 flux remotely. These spectral bands are already available on several operational satellite sensors (e.g., SeaWiFS, MODIS, and MERIS). However, before these previously undocumented relationships between indices $[(\rho_{RedEdge})^{-1} - (\rho_{NIR})^{-1}]$ and $[(\rho_{Green})^{-1} - (\rho_{NIR})^{-1}]$ and canopy photosynthesis can be employed for remote assessment of CO_2 fluxes, more work is needed to answer the questions about the accuracy of estimating diurnal CO_2 variation as well as the application of the technique for other vegetation types.

[17] **Acknowledgments.** This research was supported partially by the U.S. Department of Energy: (a) EPSCoR program, Grant No. DE-FG-02-00ER45827 and (b) Office of Science (BER), Grant No. DE-FG03-00ER62996. We acknowledge the use of facilities and equipment provided by the Center for Advanced Land Management Information Technologies (CALMIT) and the Conservation & Survey Division, University of Nebraska-Lincoln. We also wish to thank Rick Perk, Jared Burkholder, and Jeff Moon for assistance with data collection. This paper has been assigned Journal Series No. 13865, Agricultural Research Division, University of Nebraska-Lincoln.

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