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IMPACT OF SPECTRAL RESOLUTION ON SOLAR INDUCED FLUORESCENCE AND REFLECTANCE INDICES FOR MONITORING VEGETATION

L.A. Corp¹, E.M Middleton², Y.B. Cheng², P.K. Entcheva Campbell³, K.F. Huemrich³

¹Science Systems and Application Inc., Lanham, MD 20706

²Biospheric Sciences Branch, NASA/GSFC, Greenbelt, MD 20771

³JCET, University of Maryland, Baltimore, MD 21250

ABSTRACT

This study examines the impact of spectral resolution on red-edge reflectance (R) and Fraunhofer Line Depth (FLD) derived fluorescence (F) from vegetation. The goal of this investigation is to present data describing net canopy CO₂ exchange (A_{net}) of corn (*Zea mays* L.) under variable N supply and present considerations for both fluorescence and reflectance sensing methodologies to remotely quantify this key regulator of ecosystem/biome productivity. A number of R indexes were investigated and consistent relationships were evident between red-edge R and R derivative (D) indexes to indicators of crop growth and condition. Through Gaussian FWHM spectral broadening of the native 3 nm data in intervals from 10 nm to 50 nm, it was determined that correlations were maintained between the top two performing indexes (D_{max}/D_{744} , R_{800}/R_{750}) and their respective measures of crop condition (A_{net} , C:Chl) up to a 20 nm spectral resolution. Adaxial corn leaf R was obtained from three spectrometers operating in unison with optical fibers bundled together enabling NADIR measurement of leaf R at five spectral resolutions ranging from 0.2 nm to 5 nm. In general, the increased band depth of high spectral resolution data allowed for more accurate SIF retrievals with improved relationships to plant biophysical parameters. From this investigation we conclude that indices calculated from both R and F data types supplied useful information for modeling nitrogen use for carbon sequestration by vegetation.

Index Terms— Remote Sensing, Vegetation, Reflectance, Fluorescence.

1. INTRODUCTION

A major goal of the U.S. Carbon Cycle Science Program is to monitor the vegetation processes related to carbon dioxide (CO₂) uptake. Biological carbon (C) sequestration is driven by nitrogen (N) availability since N is a key component in photochemical enzymes and light harvesting pigments. Large scale monitoring of vegetation processes are currently possible only with remote sensing systems that rely heavily on passive reflectance (R) information. R indices particularly in the red edge have demonstrated

significant relationships to leaf and canopy chlorophyll (Chl) content [1]. Fluorescence (F) emitted from chlorophyll has been extensively used for the elucidation of the photosynthetic pathways and is more directly linked to photochemical reactions. However, remote utilization of the relatively weak F signal in C cycle science has been elusive. Recent advances in high resolution spectral radiometers have enabled mathematical manipulations based on the Fraunhofer Line Depth (FLD) principle to isolate the solar induced F (SIF) signal from the high resolution R continuum [2-8]. Here we will present data describing leaf and canopy biophysical changes induced by N driven C cycling in corn (*Zea mays* L.) and present considerations for both F and R sensing methodologies to remotely quantify key regulators of ecosystem/biome productivity.

2. METHODS

The experiment site located at USDA Beltsville Agricultural Research Center is part of an intensive multi-disciplinary project entitled Optimizing Production Inputs for Economic and Environmental Enhancement (OPE). An intensive ground sampling protocol was initiated in 2001 across the nitrogen test site and within wooded riparian wetland. The corn N test site consisted of 12 plots large enough to capture the spatial variability of crop and soil parameters with treatment groups of 280, 140, 70, and 0 kg N / ha, which provided a range of plant growth and condition. Leaf and crop biophysical parameters along with canopy R were acquired at the grain fill (R3) reproductive stage. These measurements included pigment contents, leaf optical properties, total leaf C:N, and maximum photosynthetic rate (A_{max}). *In situ* georeferenced canopy measurements were comprised of; leaf area index (LAI), light use efficiency (LUE, $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1} \text{ aPAR}^{-1}$), grain yield (kg/ha), and canopy R. Measurements occurred *in situ* where possible, otherwise uppermost fully expanded leaves or 3rd leaf from terminal were excised from the plant canopy.

2.1 LUE and Canopy Gas Exchange

Leaf photosynthetic capacity (A_{max}) was determined *in situ* with a Li-Cor 6400 photosynthetic system. A_{max} was determined under controlled conditions of 1660 $\mu\text{mol m}^{-2}$

s-1 PAR, saturating CO₂ concentration (1000 ppm), controlled leaf temperature (22°C), and relative humidity (~35%). LUE was calculated as the ratio of C secured by vegetation per unit of absorbed photosynthetic active radiation as determined from leaf optical properties with the ASD FieldSpec Pro coupled to LI-1800 Integrating sphere. The plant gas exchange calculator (GCX) is a comprehensive graphical user interface driven leaf/canopy gas exchange model that used key environmental variables such as LAI, PAR, CO₂, air temperature, relative humidity, wind speed, and soil moisture on maize to scale from the leaf A_{\max} observations to canopy gas exchange A_{net} .

2.2 Spectral Reflectance

A spectroradiometer (ASD-FR FieldSpec Pro, Analytical Spectral Devices, Inc., Boulder, CO) was used to measure canopy radiance 1 m above plant canopies with a 22° field of view and a 0° nadir view zenith angle. A second cross-calibrated ASD radiometer was used in a similar viewing geometry over a Spectralon reference panel (Labsphere, North Sutton, NH) to simultaneously track changes in solar irradiance. The ASD spectroradiometers use a 512 channel silicon photodiode array for the visible portion of the spectrum overlaid with an order separation filter to provide a 3 nm Full-Width at Half Maximum (FWHM) spectral resolution sampled at a 1 nm.

Adaxial corn leaf R was obtained from freshly excised leaves (4th from terminal) with three spectrometers operating in unison; the ASD-FR FieldSpec Pro, the USB4000 (Ocean Optics, Inc., Dunedin, FL), and a third custom designed PI spectrometer (Princeton Instruments, Trenton, NJ). The USB4000 spectrometer was configured with a 3648 element linear silicon CCD array and bandpass filters for a 1.5 nm (FWHM) spectral resolution sampled at a 0.19 nm over the operating range from 350 nm to 1000 nm. The third system consisted of PI Max II 1003HB fast gated intensified CCD (1024 x 1024 pixel array) imaging system coupled to the PI Acton SpectraPro SP-2356 imaging spectrograph containing a triple grating turret. The software driven mechanical turret allowed rapid interchange between the following three gratings; the first grating with a groove density of 50 G/mm

yielding a spectral resolution of 6 nm sampled at a 0.818 nm interval, the second a 300 G/mm grating yielding a spectral resolution of 1 nm sampled at a 0.131 nm interval, and the third a 1200 G/mm grating yielding a spectral resolution of 0.2 nm sampled at a 0.023 nm interval. The optical fibers from the three spectrometers were bundled together and attached to an optical breadboard at a 10° relative solar azimuth and 10 cm to leaf sample holder. The optical breadboard was attached to a tripod and periodically adjusted to maintain direct solar illumination over the course of the experiment.

2.3 FLD Derived SIF

An adaptation of the FLD principle was applied to discriminate the relatively weak in situ vegetation Chl F in-fill of the telluric O₂ bands located at 688 nm and 760 nm [9]. The following equations of the FLD principle were used to obtain canopy R and F from vegetated surfaces:

$$R_d = (c-d)/(a-b) \quad F_d = d - R_b = (ad - cb)/(a-b)$$

Here 'b' and 'a' represent the reference panel radiance in and out of each O₂ feature, respectively, and 'c' and 'd' represent the target radiance. The accuracy of FLD algorithm was enhanced with absorption feature analysis and continuum removal to adjust the within feature variables 'b' and 'd' making use of multiple wavebands from high resolution spectra.

3. RESULTS

3.1 Biophysical Summary of Field Corn Growth

Multi-year analysis of field corn growth indicated that leaf parameters (Chl, A_{\max} , LUE) and crop parameters (LAI, grain yield, A_{net}) increased with N level (Table 1). LAI, C:N, Chl, and Chl a:b were similar for the two N fertilization rates ≥ 140 kg N/ha, whereas significant decreases were obtained for treatments ≤ 70 kg N/ha. The leaf LUE measured parameter trended toward higher values as N level increased while the GCX modeled net canopy photosynthesis (A_{net}) indicated significant reductions with N supply.

TABLE 1. Biophysical Summary of N treatment effects on field corn growth.

Treatment (kg N/ha)	Leaf and Canopy Parameters					Canopy R Indices ^a				
	Chl	C:N	A_{\max}	LUE	A_{net}	D_{\max}/D_{744}	D_{730}/D_{706}	R_{800}/R_{750}	PRI	F_{688}/F_{760}
280	55.6 a ^b	14.1 a	35.6 a	.0217 a	61.4 a	1.43 a	2.53 a	1.17 a	-0.080 a	0.92 a
140	53.5 a	14.9 a	33.4 a	.0208 ab	58.8 b	1.47 a	2.38 ab	1.16 a	-0.085 b	1.00 a
70	49.9 b	17.5 b	30.6 b	.0196 ab	53.4 c	1.58 a	2.24 b	1.14 b	-0.087 b	1.13 b
0	29.7 c	22.0 c	27.8 c	.0185 b	34.4 d	2.56 b	1.31 c	1.09 c	-0.097 c	1.53 c
LSD _{.05}	3.26	1.16	2.57	0.0028	2.42	0.170	0.205	0.013	0.003	0.125

^aR and FLD derived F indices were calculated from 3nm spectral resolution data obtained over the crop canopy (2004 - 2007, n=265).

^bWithin group column-wise means with the same letter are not separable by a repeated measures mixed model ANOVA_{LSD.05}.

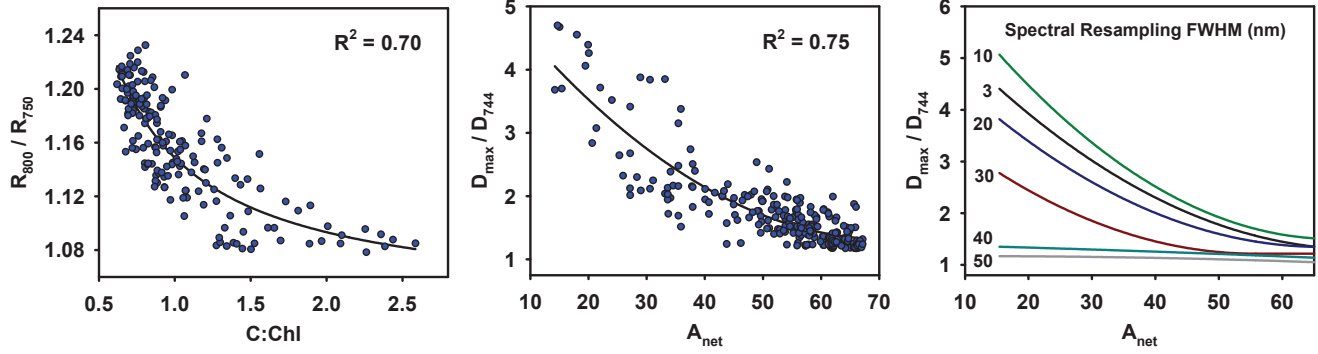


Figure 1. Relationships between corn canopy reflectance (R) and derivative (D) indexes (3 nm spectral, 1 nm sampling resolution, $n = 265$) to C related crop parameters. Gaussian FWHM spectral re-sampling was used to simulate the impact of band broadening from 3 nm to 50 nm on algorithm performance.

3.2 Spectral Remote Sensing of C Parameters with R

A number of R indices surveyed from the literature and developed by members of this group were evaluated based on consistent performance over measurement scales and reproducible correlations to biophysical measures of plant growth and condition. Table 1 summarizes the top performing R indices for differentiating plant growth and condition as induced by varying N application rates. Several R indices including but not limited to the Primary Physiological Index [$PRI = (R_{530} - R_{550}) / (R_{530} + R_{550})$] differentiated three of the four N fertilization rates [10]. Although R derivative index D_{max}/D_{744} did not perform well in separating N levels with the ANOVA model it did yield the highest correlations of the indices surveyed to the carbon parameters C:N and A_{net} (Fig. 1). Also, the simple ratio R_{800}/R_{750} performed well with several significant correlations to crop parameters. A Gaussian FWHM spectral re-sampling with a fourth order polynomial smoothing algorithm was applied to the canopy R spectra to simulate a range of spectrometer resolutions from 3 nm to 50 nm. The quadratic regression statistics indicated that a subtle spectral coarsening to 10 nm provided a slight

improvements in correlations of D_{max}/D_{744} to A_{net} and R_{800}/R_{750} to C:Chl while spectral coarsening > 20 nm significantly deteriorated both relationships.

3.3 FLD Retrieval of SIF

The modified FLD algorithm applied to multiple year canopy radiance spectra acquired with the ASD-FR FieldSpec Pro spectral-radiometer was able to provide F_{688} retrievals from the $O_{2\beta}$ absorption feature in the range of 4 to 6 $mWm^{-2}nm^{-1}sr^{-1}$ and F_{760} retrievals from the $O_{2\alpha}$ absorption feature in the range of 6 to 8 $mWm^{-2}nm^{-1}sr^{-1}$. ANOVA_{LSD0.05} analysis applied to the passive SIF ratio F_{688}/F_{760} indicated statistical separation in three of the four N groups (Table 1).

High spectral resolution leaf observations indicated increased Fraunhofer band depth in the telluric $O_{2\beta}$ and the $O_{2\alpha}$ absorption features (Figure 2) with the solar H_{α} Fraunhofer feature at 656.6 nm only apparent in irradiance spectrums with resolutions ≥ 1.5 nm. The $O_{2\alpha}$ band depth ranged from 0.84 ± 0.021 at a 0.2 nm spectral resolution to 0.09 ± 0.01 at 5 nm spectral resolution. The $O_{2\beta}$ feature band depth was 0.35 ± 0.025 at a 0.2 nm spectral resolution

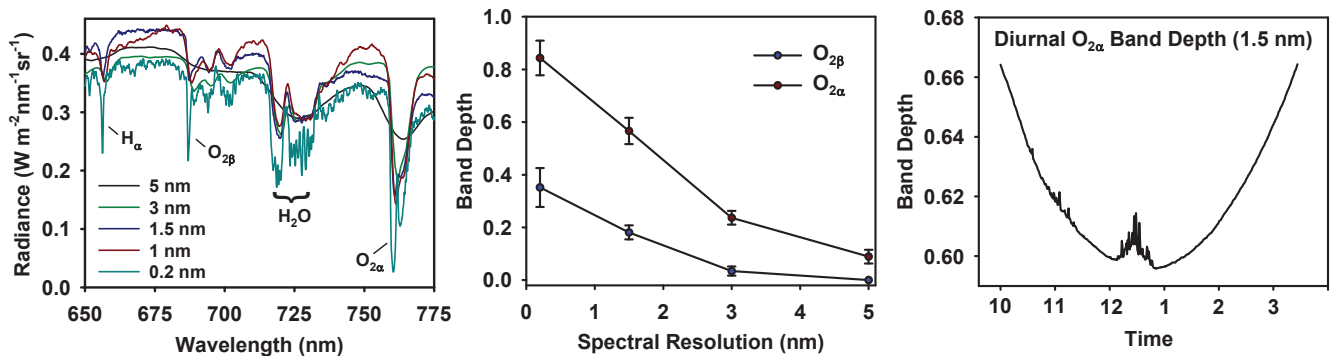


Figure 2. Solar irradiance at five spectral resolutions indicates decreasing band depth with spectral resolution. Diurnal variation is evident for the telluric O_2 features, with reduced band depth corresponding to the shortest atmospheric optical path length occurring at mid-day.

and was not distinguishable in the 5 nm spectral data. Significant diurnal variations in band depth were observed for both absorption features. Band depth varied as much as 20% in the $O_{2\beta}$ feature and 10% in the $O_{2\alpha}$ feature (1.5 nm resolution) indicating a strong need for simultaneous reference measurements (Figure 2). In general, the increased band depth of high spectral resolution data allowed for more accurate SIF retrievals.

4. CONCLUSION

A number of significant relationships were evident in both R and SIF indexes to the biophysical changes in corn induced by N application rates. Consistent relationships were evident between a number of red-edge R and R derivative (D) indexes to indicators of crop growth and condition; most notable, leaf C relative to total chlorophyll (C:Chl), total leaf C:N, A_{net} , and light use efficiency (LUE). Through Gaussian FWHM spectral broadening of the native 3 nm data in intervals from 10 nm to 50 nm, it was determined that correlations were maintained between the top two performing indexes (D_{max}/D_{744} , R_{800}/R_{750}) and their respective measures of crop condition (A_{net} , C:Chl) up to 20 nm after which significant deteriorations in correlations were observed. Significant separation of crop condition was also observed with the FLD derived SIF ratio F_{688}/F_{760} from canopy R spectra. Results presented here indicate significant relationships exist between hyperspectral R derivative indices and FLD narrow band indices to C related vegetation parameters. These results advocate the application of hyperspectral sensors for remotely monitoring carbon cycle dynamics in terrestrial ecosystems.

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