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Remote estimation of canopy chlorophyll content in crops

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[1] Accurate estimation of spatially distributed chlorophyll content (Chl) in crops is of great importance for regional and global studies of carbon balance and responses to fertilizer (e.g., nitrogen) application. In this paper a recently developed conceptual model was applied for remotely estimating Chl in maize and soybean canopies. We tuned the spectral regions to be included in the model, according to the optical characteristics of the crops studied, and showed that the developed technique allowed accurate estimation of total Chl in both crops, explaining more than 92% of Chl variation. This new technique shows great potential for remotely tracking the physiological status of crops, with contrasting canopy architectures, and their responses to environmental changes. **Citation:** 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.

1. Introduction

[2] The importance of studying chlorophyll content (Chl) in vegetation has been recognized for decades [e.g., *Danks et al.*, 1984]. Long- or medium-term changes in Chl can be related to photosynthetic capacity (thus, productivity), developmental stage, and canopy stresses [e.g., *Ustin et al.*, 1998]. It was suggested that Chl may appear to be the community property most directly relevant to the prediction of productivity [*Lieth and Whittaker*, 1975].

[3] Due to the synoptic view provided by airborne and space-borne sensors, remote sensing has the potential of estimating Chl on a regional and global basis. Changes in leaf Chl produce large differences in leaf reflectance and transmittance spectra, however, canopy reflectance is also strongly affected by other factors (e.g., canopy architecture, Chl distribution into the canopy, leaf area index (LAI), soil background) that mask and confound changes in canopy reflectance caused by leaf Chl. It makes Chl retrieval at canopy level complicated and challenging. Several remote sensing techniques using reflectance in the red and near-infrared (NIR) spectral regions have been proposed to estimate Chl in leaves and canopies. Saturation of red reflectance at intermediate to high Chl [e.g., *Kanemasu*, 1974; *Buschmann and Nagel*, 1993] limits the applicability of such techniques. Other studies have shown that reflectance in the green and red edge regions is sensitive to a wide range of Chl [*Thomas and Gaussman*, 1977; *Buschmann and Nagel*, 1993; *Gitelson et al.*, 1996a, 1996b]. Vegetation indices based on these spectral regions have been developed and used successfully [e.g., *Daughtry et al.*, 2000; *Broge and Mortensen*, 2002; *Dash and Curran*, 2004], but they have been tested under single-species canopies, and their calibration coefficients may remain species-specific.

[4] Recently, a conceptual model that relates remotely sensed reflectance with pigment content in different media (leaves, crop canopy and phytoplankton) was developed and used for the non-destructive estimation of Chl [*Gitelson et al.*, 2003a], carotenoids [*Gitelson et al.*, 2002] and anthocyanins [*Gitelson et al.*, 2001] in higher plant leaves, LAI in maize canopy [*Gitelson et al.*, 2003b] and Chl concentration in productive waters [*Dall'Olmo et al.*, 2003; *Dall'Olmo and Gitelson*, 2005]. In this study we investigated the applicability of this conceptual model for the remote estimation of Chl in maize and soybean crops, which have very different leaf structure and canopy architecture.

2. Methods

[5] This study took advantage of an established research facility, which is part of the Carbon Sequestration Program at the University of Nebraska-Lincoln. The research facility consists of three agricultural fields of approximately 65-ha each; it locates at around Lat 41.175 N, Long 96.425 W. One field was planted with maize continuously since 2001 under irrigation. The other two fields are in a maize-soybean rotation under irrigated and rainfed conditions, respectively. The study took place in 2001 through 2003 growing seasons.

2.1. Leaf Level Chlorophyll Content

[6] Chl of 65 maize and 17 soybean leaves collected in the fields during the growing season of 2002, ranging from yellow to green in color, was measured analytically and estimated non-destructively using leaf reflectance [*Gitelson et al.*, 2003a]. Reflectance measurements were collected in the range 400 to 900 nm using a black plastic polyvinyl chloride leaf clip, with a 2.3-mm diameter bifurcated fiber-optic attached to both an Ocean Optics USB2000 spectroradiometer and to an Ocean Optics LS-1 tungsten halogen light source. With the leaf clip, individual leaves are held with a 60° angle relative to the bifurcated fiber-optic. A Spectralon reflectance standard (99% reflectance) was scanned for each leaf sample. The reflectance factor at each wavelength was calculated as the ratio of upwelling leaf radiance to the upwelling radiance of the standard, and

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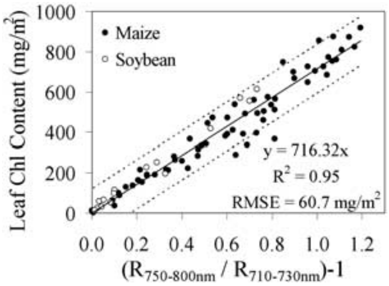

Figure 1. Linear relationship between Chl in maize and soybean leaves vs. the model ($R_{NIR}/R_{red\ egde}$) − 1.

averaged across 10 separate scans made for each leaf. All scans were corrected for the instrument's dark current. After spectral readings, the measured areas of leaves were punched and total Chl (*a* and *b*) was determined analytically. It was extracted with 80% acetone, from circular leaf punches with a 1 cm diameter. Pigment content was determined using a Cary 100 Varian spectrophotometer and equations by *Porra et al.* [1989].

[7] Leaf Chl obtained analytically was related to the model ($R_{750-800}/R_{710-730}$) − 1, where $R_{750-800}$ and $R_{710-730}$ are reflectances in the NIR and red edge ranges, respectively [*Gitelson et al.*, 2003a]. The model allowed Chl estimation with Root Mean Square Error (RMSE) < 61 mg/m^2 (Figure 1).

2.2. Canopy Level Chlorophyll Content

[8] Spectral reflectance measurements of upper canopy leaves, Chl_{upper}, were collected biweekly during the growing seasons of 2001, 2002, and 2003. Chl of each leaf was then estimated applying the above mentioned calibration (Figure 1). Total Chl in the canopy was estimated as $Chl_{est} = Chl_{upper}$*green LAI; green LAI was determined destructively (details by *Gitelson et al.* [2003b]). To test whether Chl_{upper} is representative of the entire canopy Chl, we compared Chl_{est} with measured total Chl content in the canopy (Chl_{meas}). To find Chl_{meas}, Chl contents of all the leaves (Chl_i^{leaf}) of 22 maize and 14 soybean plants, collected during the growing season, were measured using the non-destructive technique described earlier. Areas of each of these leaves, S_i^{leaf}, were measured with an area meter (Model LI-3100A, Li-Cor, Inc., Lincoln NE). Total Chl in the entire plant expressed as the amount of Chl per unit of ground S_g (i.e. g/m^2) was calculated as $Chl_{meas} = (\Sigma_{i=1}^{n}\ (Chl_i^{leaf} * S_i^{leaf})/S_g$, where *n* is number of leaves in each plant. The measured and estimated total Chl in the canopy were closely related (Figure 2). This suggests that total Chl in the canopy can be accurately estimated using the product of green LAI and Chl in the upper canopy leaves measured along the growing seasons of 2001, 2002 and 2003.

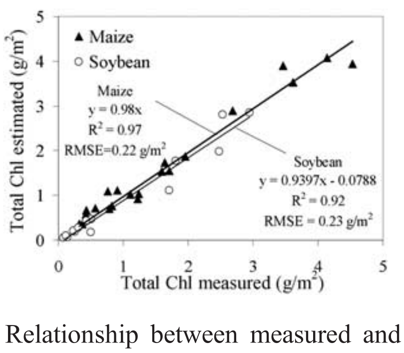

Figure 2. Relationship between measured and estimated total canopy Chl in maize and soybean. Solid lines are best fit functions.

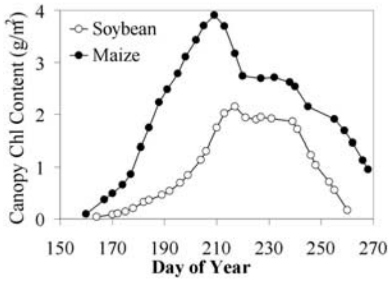

Figure 3. Temporal progression of canopy Chl in irrigated maize and soybean in 2002.

2.3. Spectral Reflectance Measurements

[9] Spectral 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.* [2004]).

3. Results and Discussion

[10] Canopy Chl content varies widely along the growing season (Figure 3). Therefore, any remote sensing technique requires a wide dynamic range for Chl assessment.

[11] The infinite reflectance of a leaf, R_∞, in which further increases in thickness result in no noticeable differences in reflectance, was found to be closely related to the reciprocal of reflectance, R^{-1} [*Gitelson et al.*, 2003a]. Thus, $R^{-1} \propto R_\infty = a/b_b$ where $a = a_{chl} + a_0$, a_{chl} is absorption coefficient of Chl, a_0 is absorption coefficient of other pigments but Chl, and b_b is backscattering coefficient.

[12] To isolate a_{chl}, the conceptual model contains reflectances at three different spectral bands [*Gitelson et al.*, 2003a]. Reflectance in the first band $R_{\lambda1}$ is maximally sensitive to Chl. To remove a_0, reciprocal reflectance in second band λ_2, such that $a_0(\lambda_2) \sim a_0(\lambda_1)$ and $a_{Chl}(\lambda_2) \ll a_{Chl}(\lambda_1)$, should be subtracted from $R_{\lambda1}^{-1}$ that gives ($R_{\lambda1}^{-1} - R_{\lambda2}^{-1}$) $\propto a_{chl}(\lambda_1)/b_b$. To remove b_b, a third spectral band λ_3 should be used where $a_{Chl}(\lambda_3) \sim 0$, and b_b controls reflectance. Thus, multiplying the difference ($R_{\lambda1}^{-1} - R_{\lambda2}^{-1}$) by $R(\lambda_3)$, we have the model that may isolate a_{Chl}:

$$\left[R(\lambda_1)^{-1} - R(\lambda_2)^{-1}\right]R(\lambda_3) \propto a_{chl}$$

[13] To find the optimal spectral bands λ_1, λ_2, and λ_3 in the model, we used a stepwise technique based on linear regression of the model vs. total Chl content in the canopy. As the first step in model tuning we found the optimal position of λ_2 using an initial λ_1^0 = 675 nm (red Chl

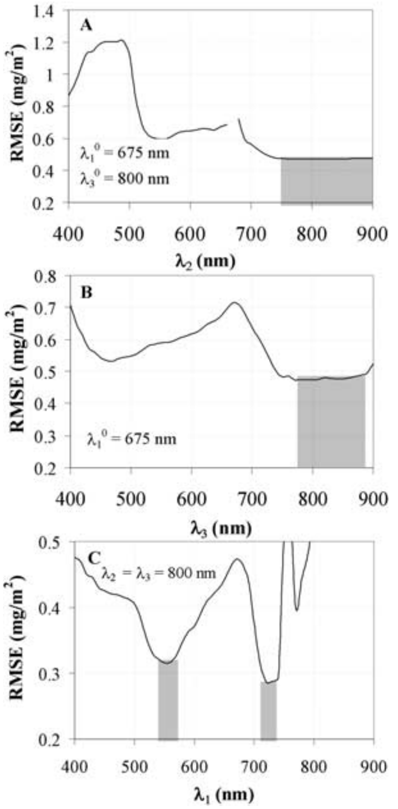

Figure 4. Three steps of model tuning for five irrigated and two rainfed maize fields measured in 2001, 2002 and 2003. RMSE was calculated for linear regression of the model $[R(\lambda_1)^{-1} - R(\lambda_2)^{-1}]R(\lambda_3)$ versus total canopy Chl content.

absorption maximum) and λ_3^0 = 800 nm ($a_{Chl}(\lambda_3) \sim 0$). RMSE of Chl estimation by the model $(R_{675}^{-1} - R_{\lambda 2}^{-1})R_{800}$ had minimal values at $\lambda_2 > 750$ nm for both species (Figure 4a for maize; soybean not shown); thus, we selected λ_2 = 800 nm.

[14] In the second step we found the optimal position of λ_3 in the model $(R_{675}^{-1} - R_{800}^{-1})R_{\lambda 3}$. RMSE of Chl estimation was minimal at 750 nm < λ_3 < 880 nm for both species (Figure 4b for maize; soybean not shown). We selected λ_3 = 800 nm. In the third step we found the optimal position of λ_1 in the model $(R_{\lambda 1}^{-1} - R_{800}^{-1})R_{800}$. RMSE of Chl estimation had two distinct minima, one in the green range (around 550 nm) and one in the red edge range (700–730 nm) (Figures 4c and 5). To verify that the above procedure does not depend on the initial values of λ_1^0 and λ_3^0, we assessed the optimal position of λ_2 for λ_1 = 710 nm and λ_3 = 800 nm. The optimal λ_2 was found in the NIR range beyond 750 nm. Therefore, two models were selected for canopy Chl estimation:

$$\text{Green Model}: \left[R_{green}^{-1} - R_{NIR}^{-1}\right] R_{NIR} = \left(R_{NIR}/R_{green}\right) - 1$$

$$\text{Red edge Model}: \left[R_{red\ edge}^{-1} - R_{NIR}^{-1}\right] R_{NIR} = \left(R_{NIR}/R_{red\ edge}\right) - 1$$

[15] To test these models in the discrete spectral bands of contemporary space-borne sensors, we used 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).

[16] Both models provided an accurate estimation of total Chl in the canopy (Figure 6). However, in these discrete spectral bands of the space-borne sensors, the calibration coefficients in both models remain species-specific. This difference between species is more pronounced in the green than the red-edge model (Figure 6). Such behavior is understandable, if one takes into account very contrasting canopy architectures and leaf structures of maize and soybean: (a) soybean has predominantly horizontal leaves while leaf angle distribution in maize is more hemispherical; (b) Chl in adaxial surface of soybean leaves is higher than Chl in maize for the same leaf Chl. Thus, for the same total Chl in the canopy, $R_{NIR}^{maize} < R_{NIR}^{soybean}$ and soybean has lower reflectance in the visible spectrum; therefore, this causes higher model values for soybean than for maize.

[17] To find a spectral range where the model is non-species specific, we applied the same tuning procedure as described above for the data set containing reflectance spectra and Chl of both maize and soybean canopies (Figure 7a). The model $(R_{840-870}/R_{720-730}) - 1$ estimates

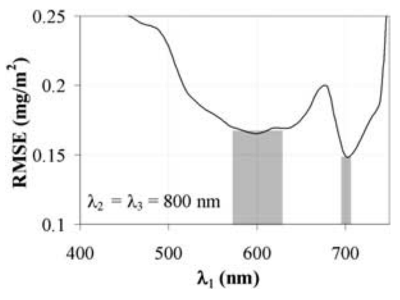

Figure 5. Third step of model tuning for λ_1 in irrigated and rainfed soybean fields measured in 2002. Tuning for λ_2 and λ_3 gave the same spectral region (750–880 nm) as in maize.

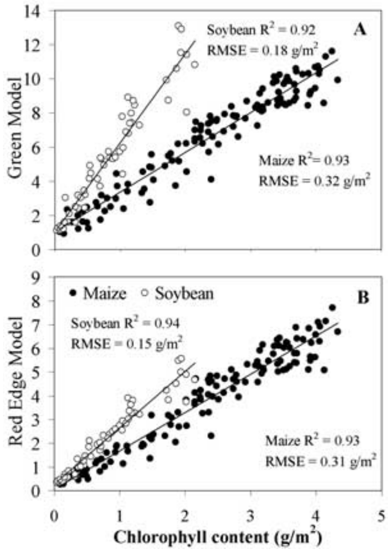

Figure 6. Remote estimates of Chl in maize and soybean. Solid lines are best fit functions.

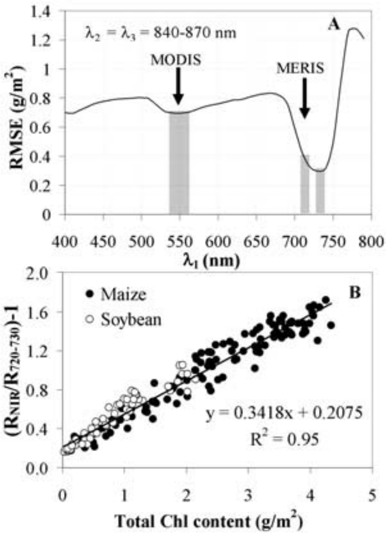

Figure 7. (a) Model tuning for maize and soybean measured in 2001–2003. Third step: λ_2 = λ_3 = 840–870 nm. Spectral bands of MODIS and MERIS used in the model are also shown. (b) The model ($R_{NIR}/R_{720-730}$) − 1 vs. canopy Chl in both species considered together. Solid line is best fit function.

Chl in the range 0.03 to 4.33 g/m^2 with a RMSE of less than 0.32 g/m^2 for both species considered together (Figure 7b). In the case of a mixed pixel containing soybean and maize, the accuracy of the green model with MODIS bands decreases (RMSE < 0.69 g/m^2; r^2 = 0.7). The accuracy of the red edge model with MERIS bands reduced slightly (RMSE < 0.41 g/m^2; r^2 = 0.89), allowing an accurate Chl estimation.

4. Conclusions

[18] Close relationships were found between the model [($R_{NIR}/R_{\lambda 1}$) − 1] and Chl in maize and soybean canopy, with λ_1 in the green and red edge spectral bands. Using these models, canopy Chl can be accurately estimated by current space-borne sensors such as MODIS, MERIS, Landsat TM and ETM+. For maize and soybean crops with very different canopy architectures and leaf structures, the models showed to be species-specific in the spectral ranges of current space-borne sensors, thus different calibration coefficients may be required for different vegetation types, and estimation errors may increase under a mixed pixel scenario. It was shown that the model [($R_{NIR}/R_{720-730}$) − 1] accurately estimates Chl in such very contrasting species as soybean and maize and thus can be applied to estimate canopy Chl under a mixed pixel scenario. The wide range of canopy conditions studied (LAI, Chl, canopy architecture and leaf structure), suggests that the developed technique may also be applied for other crops. However, an extensive data base containing data from different locations and crop species is required to test the accuracy of the models, particularly under a multi-species canopy.

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