Heterogeneity of CASI-Estimated Leaf Chlorophyll in Corn: Assessment and Comparison with Ground Truth from L'Acadie GEOIDE Experimental Site

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Abstract

As a part of GEOIDE project for precision farming, collaboration between York University (Toronto) and Agriculture and Agri-Food Canada (St-Jean-sur-Richelieu) has focussed on the evaluation of the potential of CASI hyperspectral data to characterize the nitrogen status of corn canopies, and to assess the consequences of adjusting the nitrogen dose at top-dressing using the crop chlorophyll status as the surrogate measure. In this context, a canopy modelling inversion methodology has been developed using CASI airborne hyperspectral and multi-spectral canopy reflectance to generate maps of estimated leaf chlorophyll content in corn plots with a wide range of nitrogen treatments. Quantitative leaf chlorophyll estimates at the pixel level, derived from CASI, have demonstrated the existence of patterns in spatial variability both between different plots (different nitrogen treatments) and within each plot (same nitrogen treatment). Spatial heterogeneity has also been revealed by leaf chlorophyll content measurements in the laboratory from plot field sampling and with SPAD meter. Based on these observations, and given the correlation between the chlorophyll and nitrogen concentration in green vegetation, a careful analysis has been undertaken to assess chlorophyll heterogeneity over the field plots and to evaluate the correspondence between airborne and field measures of pigment, and by inference, nitrogen. This airborne information may prove an indicator of spatial variability of nitrogen both in the crop and the underlying soil.

1. Introduction

Spatial heterogeneity in crop pigment status at any particular stage in the growth cycle can be a consequence of several crop and soil variables, such as soil condition, nutrient imbalances, and disease. Crop response variability within a field is controlled by the spatio-temporal distribution of soil physical and chemical properties; therefore, its understanding needs soil and crop attributes to be sampled and observed at different scales of space and time (Cassel et al., 2000). Among these variables, nitrogen is both the most important element and the major limiting factor for crop growth and agriculture productivity. Its spatial variability is an important attribute of agricultural fields, which is traditionally assessed through soil testing and plant tissue analysis. These methods are effective but inadequate to characterise nitrogen spatial distribution because of the uncertainty due to the sampling methodology, the spatial dependence and autocorrelation of soil and crop parameters, and the substantial efforts and expenses they require (Blackmer et al., 1996; Cassel et al., 2000). However, because nitrogen concentration in green leaves is related to their chlorophyll content (Yoder and Pettigrew-Cosby, 1995), an assessment of the crop chlorophyll status could be used as a surrogate measure of nitrogen variability within the field. Indeed, nitrogen deficiency reduces foliage chlorophyll content and, consequently, changes its spectral properties: reflectance and transmittance (Walburg et al., 1982; Blackmer et al., 1994). These interrelations and interactions between nitrogen, foliage constituents and solar radiation offer unique opportunities for use of remote sensing techniques as an efficient means of analysing some biophysical and biochemical factors affecting crop canopy reflectance. Thus, reflected radiation from these canopies has been used to estimate crop chlorophyll status (Daughtry *et al.,* 2000; Haboudane et al., 2001) and, by implication, to assess nitrogen spatial variability (Blackmer *et al.,*1996).

Farmers are concerned with controlling this variability within agricultural fields, aiming to improve yield and farm productivity and to reduce input (fertilisers) costs. To this end, various precision agriculture technologies have been developed during the recent years (Moran et al., 1997). Their primary goal is to help scientists and farmers better manage agricultural fields through the use of spatially-variable application rates that are based on localised plant growth requirements and deficiencies (Cassel et al., 2000). In this context, the objectives of the present paper were (i) to explore the spatial heterogeneity of the crop chlorophyll content estimated from CASI hyperspectral images, (ii) to compare it with laboratory measurements from plot field sampling of corn leaves, and (iii) to investigate the correspondence with the expected effects of various nitrogen treatments supplied at the time of seeding and at topdressing six weeks later.

2. Data collection and processing

The study area is one of the four experimental sites of the GEOmatics for Informed Decisions (GEOIDE) project for precision agriculture. It is located near Montreal, at the Horticultural Research and Development Centre of Agriculture and Agri-Food Canada, St-Jean-sur-Richelieu, Quebec, Canada. It is known as the L'Acadie experimental research sub-station where corn was grown on four adjacent experimental fields regrouping 64 plots which represent a wide range of nitrogen levels. Four major treatments have been supplied: no fertilization (A), intermediate fertilization with uniform nitrogen application at top dressing (B) and with variable nitrogen application at top dressing based on early chlorophyll content measurements (C), and over-fertilization (D) representing a reference plot saturated in chlorophyll.

Hyperspectral images were acquired by the Compact Airborne Spectrographic Imager (CASI), flown by Centre for Research in Earth and Space Technology (CRESTech), as part of intensive field campaigns organized by GEOIDE *precision agriculture* (RES54) co-investigators during summer 2000. At the same time, relevant ground truth measurements have been carried out: (i) collection of leaf tissue for laboratory determination of leaf chlorophyll concentration, (ii) laboratory measurement of corn leaf reflectance and transmittance, (iii) chlorophyll meter (SPAD) readings of corn leaves, (iv) leaf area index (LAI) measurements, and (v) crop growth measures.

CASI images were collected in three different deployments, using two modes of operation: the *multispectral mode,* with 1 m spatial resolution and 7 spectral bands suitable for sensing vegetation properties; and the *hyperspectral mode*, with 2 m spatial resolution and 72 channels covering the visible and near infrared portions of the solar spectrum. Acquisition dates were planned to coincide with different phenological development stages covering the earliest, middle and latest periods of the growth season.

The hyperspectral digital images collected by CASI were processed to at-sensor radiance using calibration coefficients determined in the laboratory by CRESTech (Centre for Research in Earth and Space Technology). Then the CAM5S atmospheric correction model (O'Neill *et al.*, 1997) was used to transform the relative at-sensor radiance to absolute ground-reflectance. To perform this operation, an estimate of aerosol optical depth at 550 nm was derived from ground sun-photometer measurements and the Web-site of the AERONET (Aerosol Robotic NETwork) (AERONET, 2000). Reflectance spectra of asphalt and concrete within CASI imagery were used to calculate coefficients that adequately compensate residual effects of atmospheric water and oxygen absorption, and therefore to perform the flat field calibration. Data regarding geographic position, illumination and viewing geometry as well as ground and sensor altitudes were derived both from aircraft navigation data recordings and ground GPS measurements.

3. Chlorophyll predictions

Predictive relationships have been established to make chlorophyll estimations as a function of the ratio TCARI/OSAVI, where TCARI stands for Transformed Chlorophyll Absorption in Reflectance Index (Haboudane et al., 2001), and OSAVI denotes Optimized Soil-Adjusted Vegetation Index (Rondeaux *et al.,* 1996). The method is based on a combined modelling and indices-based approach to determine the crop chlorophyll content with minimal effects from underlying soil background, non-green biomass, and canopy structural development (leaf area index). It has been developed first using simulated data, and followed by evaluation in terms of quantitative predictive capability using CASI airborne hyperspectral imagery. Simulations consist in modeling leaf and canopy reflectance using *PROSPECT* (Jacquemoud and Baret, 1990) and *SAILH* radiative transfer models (Verhoef, 1984). The ratio TCARI/OSAVI has revealed a unique relationship with chlorophyll concentrations even over a wide range of LAI values (0.5 - 8). Corresponding predictive equations have been retrieved and successfully applied to CASI airborne hyperspectral images to map chlorophyll status over agricultural fields seeded with corn, and supplied with different nitrogen treatments (Haboudane et al., 2001).

4. Analysis and discussion

Field and Laboratory measurements

During each intensive field campaign, the most recently expanded leaves of four plants per experimental unit (64 plots) were brought to the laboratory in order to perform the following measurements for each leaf: chemical analysis of chlorophyll content, reflectance and transmittance determination, and SPAD measurements. The transmittance and reflectance spectra were smoothed, then used for chlorophyll content retrieval by inversion of the PROSPECT model. The correspondence between estimated and measured leaf chlorophyll content is illustrated by Figure 1. It can be seen that there is a general trend following approximately the one-by-one line, but with a fair dispersion of the points leading to a moderately good relationship between measured and retrieved values (r^2 = 0.56). The coefficient of determination increases to r^2 = 0.72 when plot average chlorophyll is considered. This unexpectedly low correlation at the leaf level could be due to the following reason: the spectral properties involved in the model inversion weren't measured exactly on the same tissue portions used for chemical analysis. Indeed, pigment concentrations are not uniform all over the corn leaf extent.

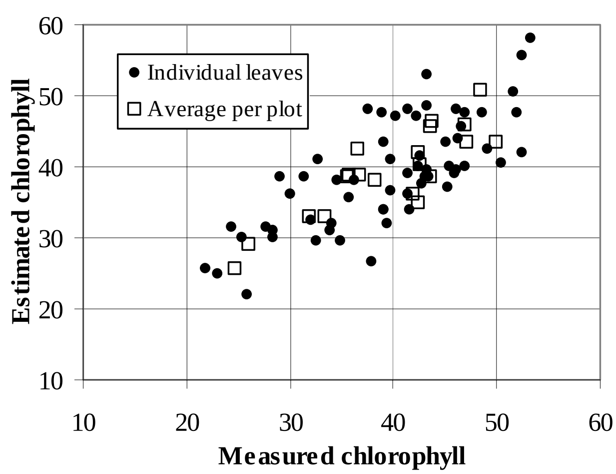

Figure 1: Comparison between lab-measured chlorophyll and estimated chlorophyll by PROSPECT inversion for the first intensive field campaign.

Because unlike laboratory analysis, field chlorophyll instruments provide rapid nitrogen assessments, we explored the relationship between leaf chlorophyll meter readings (SPAD) and plant extracted chlorophyll concentrations. Results obtained from two intensive field campaigns showed a consistent correlation between SPAD readings and laboratory-measured chlorophyll concentrations (Figure 2). Based on this dataset, the exponential fit demonstrated a slightly better coefficient of determination (r^2 = 0.84) in comparison to the linear regression (r^2 = 0.80). These correlation levels are not consistent enough to derive predictive equations for estimation of chlorophyll content from SPAD readings. This result emphasizes the calibration problems associated with an operational use of SPAD which necessitates a strict and meticulous measuring procedures. Consequently, we preferred the use of laboratory-extracted leaf chlorophyll content as ground truth for CASI-estimated chlorophyll and heterogeneity assessment.

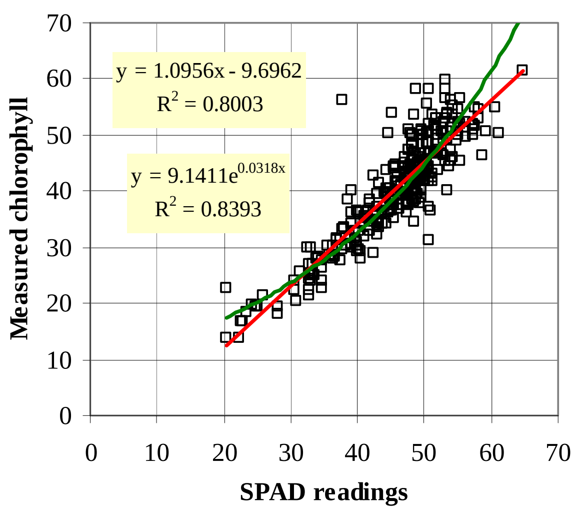

Figure 2: SPAD calibration for leaf chlorophyll concentrations of corn leaves from L'Acadie site, intensive field campaigns 2 and 3.

Inter-treatment variability

The application of the ratio TCARI/OSAVI to CASI image of the third intensive field campaign allowed the chlorophyll status of L'Acadie corn fields to be mapped (Figure 3). Beyond the bare soil plots (white tones), CASI imagery led to the distinction of three different levels of chlorophyll content: high, medium and low represented by clear, medium and dark tones, respectively. This is based only on a preliminary visual inspection of the resulting map and it doesn't reflect the effects of supplied nitrogen treatments (see section 2) on the inter-plot chlorophyll variability. Consequently, high chlorophyll content class regroups the plots which received treatments B, C, and D, medium chlorophyll class corresponds to the plots supplied with treatment A over fields 1 and 2, while low chlorophyll class gathers the plots having treatment A but only over field 3 (Figure 3). These striking differences within treatment A are caused by the nitrogen level of fields before seeding: soils in fields 1 and 2 have more nitrogen (52 and 51 kg/ha) than in field 3 (37 kg/ha). This is a consistent indicator of the important impact of soil nitrogen as a limiting or favouring factor for crop growth: a difference in nitrogen supply and/or nitrogen liberation by soil could lead to obvious differences in chlorophyll status like the one observed between field 3 (28.9 $\mu g/cm^2$) and fields 1 and 2 (41.4 $\mu g/cm^2$).

In order to appreciate the inter-treatment induced variability, mean values of estimated chlorophyll content have been extracted from CASI images for different nitrogen supplies. Table 1 attempts to compare remotely sensed estimates from CASI images (hyperspectral and multispectral) and laboratory measurements with respect to their relation with various nitrogen treatments. It shows that leaf chlorophyll content tends to increase as a function of nitrogen quantity; it doubled from treatment A (in field 3) to treatment D, and thus allowed the characterisation of the first level of spatial heterogeneity: the inter-treatment spatial variance. It supports the hypothesis that there are significant and predictable relationships between crop growth heterogeneity and soil nitrogen availability. On the other hand, it does appear that nitrogen application procedure didn't induce any significant differentiation in terms of distinct chlorophyll levels: uniform (B) and variable (C) intermediate nitrogen supplies have generated similar leaf chlorophyll classes. This suggests that nitrogen quantity variation has stronger influence on corn growth than nitrogen application procedure. Therefore, in the remainder of this analysis, corn plots with treatments B and C will be re-grouped to form one thematic class.

Table 1: Estimated and measured chlorophyll content for different nitrogen treatments, with F3 = field 3 and F1,2 = fields 1 and 2.

Treatment	laboratory	multispectral	Hyperspectral
A in F3	23.5	25.2	28.9
A in F1,2	37.4	38.6	41.4
B	46.0	46.5	47.8
C	44.9	46.8	48.1
D	48.7	47.9	48.9

In addition, Table 1 illustrates a consistent correspondence between CASI estimates and laboratory measurements, with multispectral (1 m resolution) predictions being slightly closer to laboratory measurements compared to hyperspectral (2 m resolution) estimations.

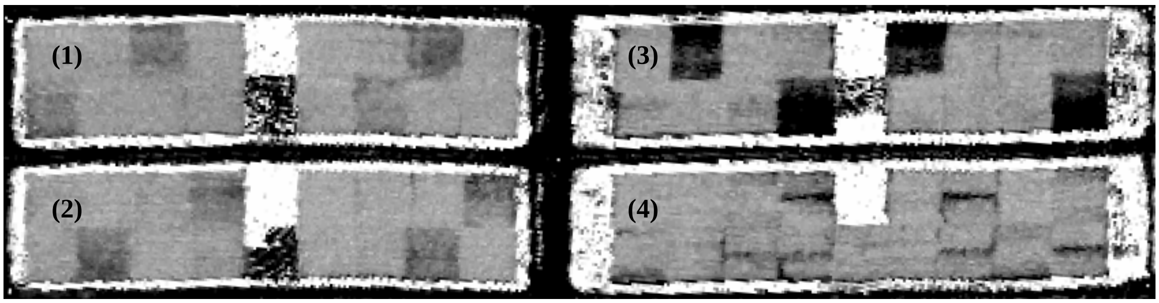

Figure 3: Chlorophyll Status of L'Acadie experimental site, retrieved from the image of August 5th, 2000. White tones represent bare soil while dark, medium and clear grey tones correspond to low, medium and high chlorophyll content, respectively.

Within-treatment variability

Statistics including mean, standard deviation, and corresponding coefficient of variation were computed in order to capture the variability both within and between plots, as well as to assess how spatial heterogeneity of chlorophyll content correlates with soil nitrogen availability. Results retrieved from laboratory analysis and CASI imagery are summarized in Table 2. Coefficient of variation, ratio of standard deviation to mean value, has been determined in order to standardise the spatial variance with respect to the mean value. In fact, it is important to note that an interpretation based only on the standard deviation could lead to confusing and erroneous conclusions. For instance, laboratory results show the same orders of magnitude of the standard deviation for all nitrogen treatment, suggesting that no inter-treatment variability is being observed despite of the clear differences in nitrogen availability. The computation of the coefficient of variation has improved the discrimination capabilities of laboratory analysis, but still there is confusion among chlorophyll classes representing intermediate (B and C) and saturated nitrogen (D) treatments. In contrast, CASI estimates demonstrate a constant and clear decrease of the standard deviation when chlorophyll content increases, indicating a gain in homogeneity of the green biomass induced by large nitrogen quantities. This is in a agreement with the expected spatial variability to result from fertilization differences: high soil nitrogen levels, generating high chlorophyll concentrations, should lead to homogeneous crop biophysical properties, therefore to lower standard deviation values, and vice versa. Table 2 clearly shows that within-treatment and inter-treatment spatial variability is better characterised from CASI imagery. Indeed, the coefficient of variation more than tripled as nitrogen fertiliser application decreased from a saturated scenario (D) to an unfertilised one (A in field 3). This kind of information is of major importance for the understanding of the link between nitrogen fertilization and spatial variability of crop biophysical variables.

Table 2: Statistic variables of chlorophyll content derived from CASI image and laboratory analysis.

Nitrogen Treatment	Mean(μg/cm²)		St. Deviation		Variation Coefficient (%)	
	Laboratory	CASI image	Laboratory	CASI image	Laboratory	CASI image
A (field 3)	23.5	25.2	6.0	4.4	25.6	17.7
A (fields 1, 2)	37.4	38.6	6.5	3.9	17.3	10.0
B + C	46.0	46.7	6.2	3.2	13.7	6.9
D	48.7	47.9	6.9	2.6	14.2	5.4

Because the chlorophyll estimates have been retrieved through the combination of TCARI and OSAVI, Table 3 is presented in order to determine which of these indices is the major source of predicted chlorophyll variability. In terms of magnitude, and except for the unfertilised plots (A in field 3), TCARI exhibits larger variations than OSAVI. Moreover, the ratio TCARI/OSAVI variations seem to be more influenced by TCARI variability, especially at high nitrogen levels. The weakness of OSAVI variability under these conditions could be in connection with the saturation of vegetation indices when leaf area index exceeds 3 in agricultural landscapes.

Table 3: Coefficients of variation of TCARI, OSAVI, and their ratio for various nitrogen treatments, with F3 = field 3 and F1,2 = fields 1 and 2.

Nitrogen treatment	Coefficient of variation		
	TCARI	OSAVI	TCARI/OSAVI
A in F3	15.0	14.4	14.5
A in F1,2	12.5	7.6	10.1
B + C	8.1	4.4	7.1
D	7.1	4.2	5.6

Corresponding spatial distribution of chlorophyll status is better illustrated by the map in Figure 4 below, where corn plots are discriminated with respect to their chlorophyll level and variability.

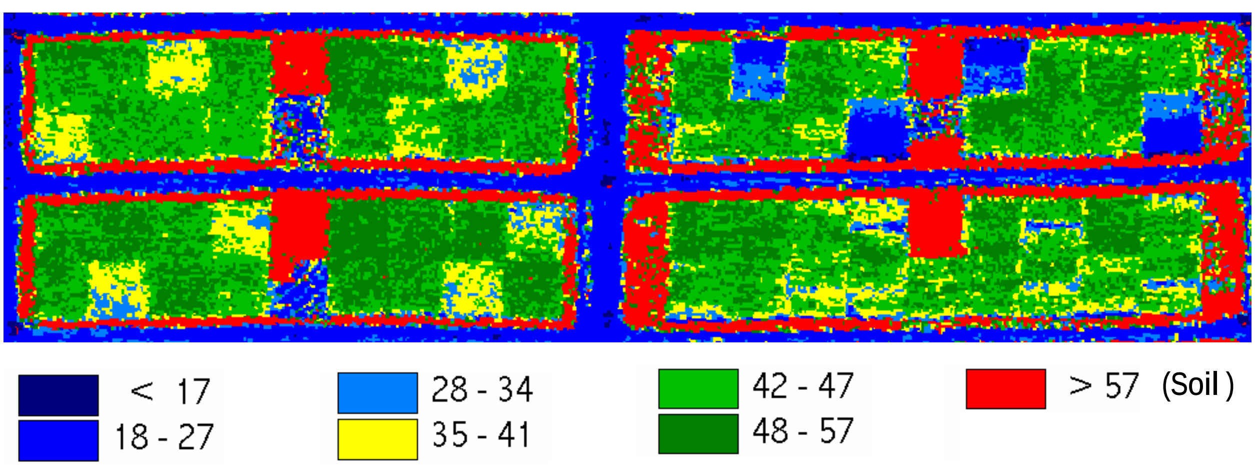

Figure 4: Map of chlorophyll status determined from CASI hyperspectral image of August 5th, 2000, for con fields at the L'Acadie experimental site (Haboudane et al., 2001). Chlorophyll estimations have been performed through the relationship between chlorophyll concentration and ratio TCARI/OSAVI.

Map texture illustrates the spatial pattern caused by the differences in nitrogen supply. This patterning has important consequences for the understanding of plant productivity and its dependence on spatial variability of soil physical and chemical properties. It expresses a time-specific status of the complex soil-crop conditions. Moreover, such information is of great importance for an effective crop management that targets both profitability optimisation and environment protection during the growing season. It will help farmers balancing the competing goals of supplying enough nitrogen to the crops while limiting its loss to the environment.

5. Conclusion

This study demonstrated the potential of airborne hyperspectral reflectance data for detecting and characterising the spatial heterogeneity of pigment content in corn canopies at the meter spatial scale using the CASI sensor. Estimates using modeling and indices-based approach have shown that chlorophyll content had responded to the spatial changes in soil nitrogen availability. Thus, characterisation of the spatial distribution of crop canopy hyperspectral reflectance could form a basis for developing technologies for variable nitrogen supply in agricultural fields, in a sense that leaf chlorophyll content is an indicator of both soil nitrogen availability and plant nitrogen status. The paper has also presented and discussed the issues related to leaf chlorophyll modeling (PROSPECT) and chlorophyll meter readings (SPAD) in respect to their agreement with plant tissue analysis in the laboratory.

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References

AERONET (2000) Ground-based remote sensing aerosol network, at the *Web-site address:* http://aeronet.gsfc.nasa.gov:8080/

Blackmer, T. M., Schepers, J. S., and Varvel, G. E. (1994), Light reflectance compared with other nitrogen stress measurements in corn leaves. *Agron J*. 86: 934-938.

Blackmer, T. M., Schepers, J. S., and Varvel, G. E., and Walter-Shea, E. A. (1996), Nitrogen deficiency detection using reflected shortwave radiation from irrigated corn canopies. *Agron. J*. 88: 1-5.

Cassel, D.K., Wendroth, O., and Nielson, D. R. (2000). Assessing spatial variability in an agricultural experiment station field: opportunities rinsing from spatial dependence. *Agron. J*. 92: 706-714.

Haboudane, D., Miller, J. R., Tremblay, N., Zarco-Tejada, P. J., and Dextraze, L. (2001). Integration of hyperspectral vegetation indices for prediction of crop chlorophyll content for application to precision agriculture, *Remote Sens. Environ. (submitted*).

Jacquemoud, S., and Baret, F. (1990), Prospect: A model for leaf optical properties spectra. *Remote Sens. Environ*. 34: 75-91.

Moran, M. S., Inoue, Y., and Barnes, E. M. (1997), Opportunities and limitations for image-based remote sensing in precision crop management. *Remote Sens. Environ*. 61: 319-346.

O'Neill, N.T., Zagolski, F., Bergeron, M., Royer, A., Miller, R.J. and Freemantle, J. (1997), Atmospheric correction validation of CASI images acquired over the BOREAS southern study area. *Canadian Journal of remote Sensing.* 23: 143-162

Rondeaux, G., Steven, M., and Baret, F. (1996), Optimization of soil-adjusted vegetation indices. *Remote Sens. Environ*. 55: 95-107.

Yoder, B. and Pettigrew-Cosby, R. E. (1995) Predicting nitrogen and chlorophyll content and concentrations from reflectance spectra (400-2500 nm) at leaf and canopy scales. *Remote Sens. Environ*. 53: 199-211.

Verhoef, W. (1984), Light scattering by leaf layers with application to canopy reflectance modeling: The SAIL model. *Remote Sens. Environ*. 16: 125-141.

Walburg, G., Bauer, M. E., Daughtry, C. S. T., and Housley, T. L. (1982). Effects of nitrogen nutrition on the growth, yield, and reflectance characteristics of corn canopies. *Agron. J*. 74: 677-683.