Indices-based Approach for Crop Chlorophyll Content Retrieval from Hyperspectral Data

Driss Haboudane
LERTG, Université du Québec à Chicoutimi (UQAC)
Chicoutimi, Quebec, Canada
Driss_Haboudane@uqac.ca
John R. Miller
Department of Earth and Space Science & Engineering
York University, Toronto, Ontario, Canada
jrmiller@yorku.ca

Nicolas Tremblay & Philippe Vigneault
Centre de recherche et développement en horticulture
Agriculture and Agri-Food Canada
Saint-Jean-sur-Richelieu, Quebec, Canada
tremblayna@agr.gc.ca
vigneaultp@agr.gc.ca

***Abstract*—This study aims at using forward model simulations and ground-measurements (biophysical and spectral) to estimate chlorophyll concentration from hyperspectral data and imagery. Its specific objectives were: (i) to evaluate various combinations of indices as estimators of chlorophyll content from simulated spectra (PROSPECT and SAILH); (ii) to establish chlorophyll predictive equations using spectral indices determined from field spectra and corresponding chlorophyll concentrations; (iii) to assess the effect of crop type (corn and wheat) on these relationships; and (iv) to validate and compare the indices' prediction capability using hyperspectral images and ground truth measurements. Hence, intensive field campaigns were organized during the growing seasons of 2000, 2004, and 2005 in order to collect ground spectra and corresponding leaf chlorophyll content values as well as crop growth measures. The relationships between leaf chlorophyll content and combined optical indices have shown similar trends for both PROSPECT-SAILH simulated data and ground measured datasets, indicating that both spectral measurements and radiative transfer models hold comparable potential for quantitative retrieval of crop foliar pigments. The dataset used showed that crop type had a clear influence on the establishment of predictive equations as well as on their validation. Moreover, corn and wheat data have led to contrasting agreement between estimated and measured chlorophyll contents even for the same predictive algorithm. Indices TCARI/TRDVI and TCI/TRDVI seem to be relatively consistent and more stable as estimators of crop chlorophyll content.**

Keywords: hyperspectral, combined indices, chlorophyll estimation, chlorophyll content, PROSPECT-SAILH, crop type effect, precision agriculture

I. INTRODUCTION

The assessment of crop canopy health-status, abundance, and vigor is important for understanding the functioning of agro-ecosystems and modeling crop development processes. Deficiency in any essential nutrient strongly impacts crop growth and yield. Therefore, measurement of crop biophysical variables is required for monitoring crop development patterns, and improving yield quality by site-specific application of fertilizers. One of the most important variables is chlorophyll content which is used by agronomists and farmers to make important management decisions at critical growth stages (e.g., nitrogen supply). Its concentration in crop leaves depends to a great extent on soil nitrogen availability and on crop nitrogen uptake. Previous research activities have developed approaches to estimate vegetation chlorophyll content from remotely sensed data using physically-based models or spectral indices. However, no studies have investigated the use of different indices combinations nor evaluated the use of predictive equations established from laboratory- and ground-measured data (pigments and spectra).

Previous studies have used laboratory analysis, field measurements and remotely sensed data to develop approaches for chlorophyll based on either the inversion of physically-based models ([1], [2], [3]) or improved relationships between chlorophyll concentration and spectral indices ([4], [5]). Physically-based models are based on simulation of canopy reflectance, and creation of quantitative relationships between remotely sensed data and canopy attributes (LAI, Chlorophyll content, etc.) for inversion purposes. Approaches using spectral indices rely on semi-empirical relationships between laboratory-measured chlorophyll concentrations and observed spectral reflectances. Their strength lies in the fact that spectral indices are easy to compute and require little expertise, especially when based on physically explainable principles.

This paper presents and discusses the use of forward model simulations and ground-measured data to make predictions of chlorophyll concentration from hyperspectral data and imagery. Its objectives were: (i) to examine the performance of various combinations of indices as estimators of chlorophyll content on the basis of simulated data using PROSPECT and SAILH; (ii) to use ground-measured spectra and corresponding laboratory-measured chlorophyll concentrations to establish chlorophyll predictive equations based on spectral indices ratios; (iii) to assess the dependency of the prediction relationships on the crop type (corn and wheat); and (iv) to compare the indices' prediction capability using CASI (Compact Airborne Spectrographic Imager) hyperspectral images and ground truth measurements.

II. MATERIAL AND METHODS

A. *Biophysical and spectral data*

The study area is the L'Acadie Experimental Research Sub-station of the Horticultural Research and Development Centre of Agriculture and Agri-Food Canada, located St-Jean-sur-Richelieu, Quebec, Canada. For the purpose of understanding nitrogen supply on crop growth, two crops (corn, wheat) were grown on different experimental or commercial fields, during three growing seasons (2000, 2004 and 2005).

During these seasons, intensive field campaigns were carried out to collect spectral and biophysical data, namely:

- hyperspectral images acquisition with the Compact Airborne Spectrographic Imager (CASI), flown by the Earth Observations Laboratory at York University, and

- a set of field and laboratory data sampled for biochemical and geochemical analysis, along with optical and biophysical measurements (leaf chlorophyll concentration, chlorophyll meter (SPAD) measurements, leaf area index (LAI), soil and crop spectra, and crop growth measures).

The CASI hyperspectral images were processed to at-sensor radiance using calibration coefficients determined in the laboratory by the Earth Observations Laboratory at York University, then transformed to absolute ground-reflectance using CAM5S atmospheric correction model. To perform this operation, an estimate of aerosol optical depth at 550 nm was derived from ground sun-photometer measurements. Data regarding geographic position, illumination and viewing geometry as well as ground and sensor altitudes were derived both from aircraft navigation data records and ground GPS measurements.

Simulated spectra were obtained using the PROSPECT model which simulates upward and downward hemispherical radiation fluxes between 400 and 2500 nm, and relates foliar biochemistry and scattering parameters to leaf reflectance and transmittance spectra ([7]). The latter were used as inputs to simulate corn canopy reflectance for a wide range of chlorophyll concentrations. These simulations were generated by the canopy model SAILH [8] which is a variant of the SAIL (Scattering by Arbitrary Inclined Leaves) model improved to take into account the hotspot effect.

B. *Vegetation and chlorophyll indices*

Numerous optical indices were developed and successfully implemented to make estimates of chlorophyll concentration from leaf optical properties ([6], [2]). They are mainly exploiting the differences in reflectance between stressed and healthy vegetation in the spectral regions of the visible and the red-edge. Nevertheless, their use to predict the canopy chlorophyll content is not appropriate because canopy reflectance is strongly influenced by the changes in plant architecture, canopy structure, and soil background optical properties. On the other hand, traditional vegetation indices have shown low correlation levels with vegetation pigments, and certain insensitivity to soil optical properties, with acceptable relationships for leaf are index (LAI) estimation from remotely sensed data. Consequently, combinations involving the so-called chlorophyll indices variations and traditional vegetation indices were proposed to minimize LAI and soil background effects and maximize the response to chlorophyll concentrations ([4], [9]). Indices used in this study are presented in Table I. This is not a review meant to gather all published chlorophyll and vegetation indices; it shows only those indices selected for use in the present paper.

TABLE I. SUMMARY OF CHLOROPHYLL AND VEGETATION INDICES ANALYZED IN THIS STUDY. USING HYPERSPECTRAL NARROW-BANDS, INDICES WERE QUANTIFIED BY THE FOLLOWING EQUATIONS WHERE R_X IS THE REFLECTANCE AT THE GIVEN WAVELENGTH "X" IN nm

Index	Formula	Reference
Chlorophyll indices		
MCARI	$[(R_{700}-R_{670})-0.2*(R_{700}-R_{550})]*(R_{700}/R_{670})$	Daughtry *et al.* (2000)
TCARI	$3*[(R_{700}-R_{670})-0.2*(R_{700}-R_{550})*(R_{700}/R_{670})]$	Haboudane et al. (2002)
TCI	$[1.2*(R_{700}-R_{550})-1.5*(R_{670}-R_{550})*\sqrt{R_{700}/R_{670}}]$	This study
TCI1	$[1.2*(R_{700}-R_{550})-1.5*(R_{670}-R_{550})]*\sqrt{R_{700}/R_{670}}$	This study
TCI2	$[1.2*(R_{700}-R_{550})-1.5*(R_{670}-R_{550})]*(R_{800}+R_{670}+0.5)/\sqrt{R_{700}}$	This study
TCI3	$[1.2*(R_{700}-R_{550})-1.5*(R_{670}-R_{550})]*(R_{700}/R_{670})$	This study
Vegetation indices		
NDVI	$(R_{800}-R_{670})/(R_{800}+R_{670})$	Rouse et al. (1974)
RDVI	$(R_{800}-R_{670})/\sqrt{(R_{800}+R_{670})}$	Rougean and Breon (1995)
SAVI	$(1+0.5)*(R_{800}-R_{670})/(R_{800}+R_{670}+0.5)$	Huete (1988)
OSAVI	$(1+0.16)*(R_{800}-R_{670})/(R_{800}+R_{670}+0.16)$	Rondeaux et al. (1996)
MSAVI	$0.5*[2*R_{800}+1-\sqrt{(2*R_{800}+1)^2-8*(R_{800}-R_{670})}]$	Qi et al. (1994)
TRDVI	$1.5*(R_{800}-R_{670})/\sqrt{(R_{800}+R_{670})+0.5}$	This study

III. RESULTS AND DISCUSSION

A. Relationships between spectral indices and chlorophyll content

To determine the most suitable combined index for leaf chlorophyll estimation, empirical regressions, with logarithmic and exponential functions, between optical ratios and chlorophyll concentrations were carried out using simulated and measured datasets. We evaluated the effect of the use of a given vegetation index on the relationship between the combined indices and chlorophyll content. Results obtained are represented in Fig. 1 where determination coefficients (R^2) of the relationship with chlorophyll-combined indices were plotted as a function of vegetation indices used. One can conclude from these results four important remarks in terms of correlation stability.

First, with simulated data, the consistency of the correlation is not influenced by vegetation indices but rather by chlorophyll indices (Fig. 1 top); indeed while TCARI yielded R^2 between 0.91 and 0.96 (except for MSAVI with $R^2 = 0.87$), the other chlorophyll indices exhibited higher R^2 values (0.96 - 1.00).

Second, with the corn-measured dataset, the variability is primarily due to vegetation indices, with two distinctive performances: NDVI and OSAVI led to relatively weaker correlations (R^2 from 0.64 to 0.81, but 0.43 for TCI2/NDVI) than the other indices (R^2 from 0.80 to 0.88) (Fig. 1 centre).

Third, with wheat-measured data, both chlorophyll and vegetation indices exert a certain control on the correlation: while TCARI seems to be the worst among chlorophyll indices (R^2 from 0.33 to 0.40), NDVI and OSAVI generated the lowest correlations among vegetation indices (R^2 from 0.23 to 0.55) (Fig. 1 bottom). Fourth, with corn and wheat measured datasets used together, strong influences are exerted by both families of indices. Thus, while TCARI and TCI3 show the best overall performance amongst chlorophyll indices, TRDVI, MSAVI and SAVI seem to perform better than the other vegetation indices (Fig. 1 bottom).

Furthermore, one can notice that, in general, the average R^2 values dropped from about 0.97 with simulated data, to about 0.85 for corn-measured data, down to around 0.56 in the case of wheat-measured data, with of course significantly lower average values for ratios involving NDVI and OSAVI. Additionally, considering both simulated and measured datasets, ratios using SAVI and TRDVI tend to be the most consistent and stable. Conversely, MSAVI did not perform as well with simulated and wheat measured data, while RDVI showed a relative weakness with corn and corn + wheat measured datasets. As a consequence, combined indices involving TRDVI were considered for further tests in the present study, namely for prediction and validation processes.

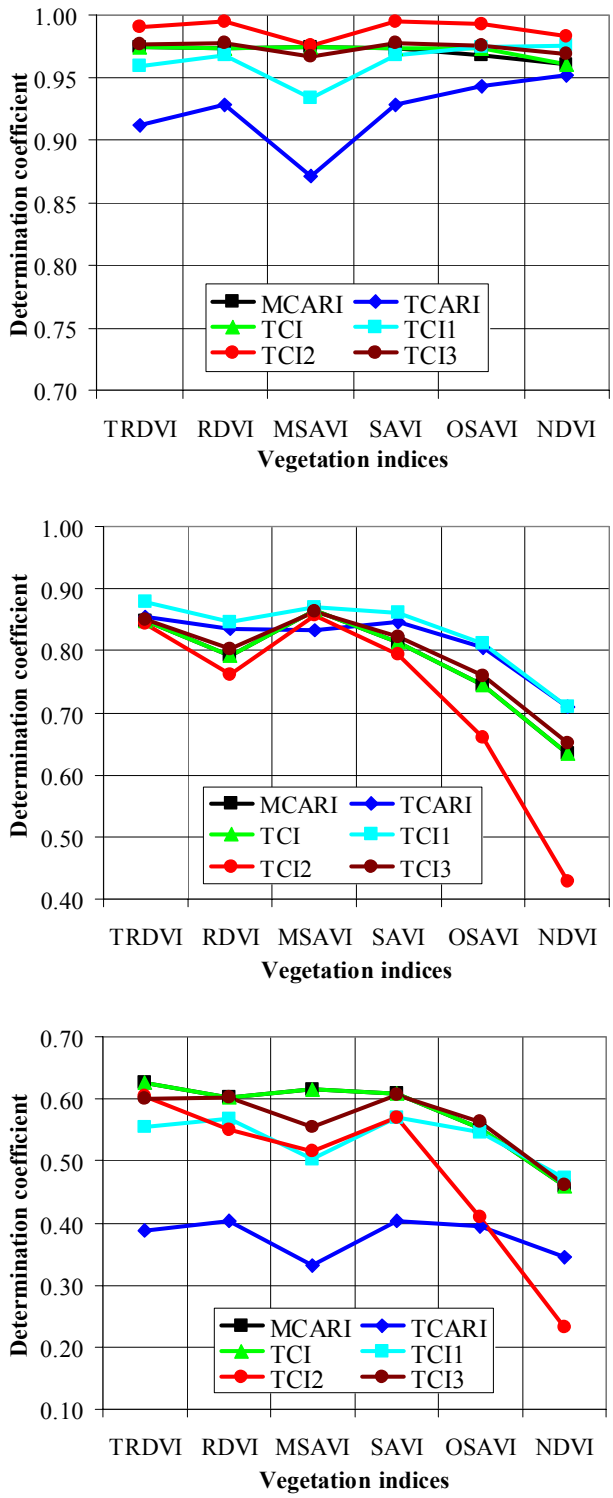

Figure 1. Determination coefficients between chlorophyll content and spectral indices ratios for various data sources: Simulated data (top), corn measured spectra (centre), and wheat measured spectra (bottom).

B. *Estimation of crop chlorophyll content and validation*

Predictive equations for different combined indices were applied to CASI images to generate maps of chlorophyll from which chlorophyll values were extracted and compared to ground truth measurements. Linear regressions were carried out to evaluate the predictive power of ratios used. Results (R^2 and RMSE) are summarized in Table II which shows contrasting results in terms of: vegetation index influence, data source, and crop-type effect. The effect of the vegetation index is illustrated by the use of OSAVI and TRDVI in combination with chlorophyll indices MCARI and TCARI. TRDVI holds a striking advantage on OSAVI, with R^2 average differences of 22%, 15.5% and 70% for MCARI, and 8.5%, 17.5% and 41% for TCARI, on validation data of corn, wheat, and corn + wheat, respectively. This difference in favor of TRDVI is corroborated by the noticeable improvement of the RMSE of the combinations using TRDVI. From Table II, it seems that datasets used to establish predictive equations had no significant impact on the agreement (R^2) between estimated and measured chlorophyll. Each index led to similar R^2 for all functions independently of data source. Conversely, the application of the equations to different crops led to very contrasting agreements between estimations and ground truth. Depending on the combined index, agreements were good to very good (R^2 = 0.52-0.80) for corn field, moderate to good (R^2 = 0.36-0.50) for wheat field, and insignificant to weak (R^2 = 0.03-0.34) when corn and wheat were considered together (Table II). This crop-type effect is confirmed by the prediction accuracy expressed in terms of RMSE.

TABLE II. DETERMINATION COEFFICIENTS AND RMSE (μg/cm^2) FOR MEASURED CHLOROPHYLL *versus* CASI-ESTIMATED CHLOROPHYLL FOR CORN, WHEAT, AND CORN + WHEAT

Indices	**R^2 and RMSE for prediction equations from**					
	Simulated data		***Corn spectra***		***Wheat spectra***	
Corn	***R^2***	***RMSE***	***R^2***	***RMSE***	***R^2***	***RMSE***
MCARI/OSAVI	0.52	12.51	0.53	7.10	0.53	20.34
TCARI/OSAVI	0.72	11.07	0.73	7.95	0.73	17.19
MCARI/TRDVI	0.67	8.53	0.68	5.81	0.68	19.10
TCARI/TRDVI	0.78	6.93	0.80	6.18	0.80	13.96
TCI/TRDVI	0.74	11.31	0.76	5.95	0.76	17.33
TCI1/TRDVI	0.75	7.98	0.76	5.72	0.76	17.46
TCI2/TRDVI	0.71	6.96	0.71	6.02	0.71	19.29
TCI3/TRDVI	0.67	8.53	0.68	5.81	0.68	19.10
Wheat						
MCARI/OSAVI	0.40	12.85	0.40	15.33	0.39	4.88
TCARI/OSAVI	0.36	7.62	0.36	9.07	0.35	5.21
MCARI/TRDVI	0.46	13.14	0.47	14.75	0.47	4.67
TCARI/TRDVI	0.43	10.12	0.43	9.01	0.43	4.81
TCI/TRDVI	0.48	7.62	0.48	10.64	0.48	4.54
TCI1/TRDVI	0.50	12.09	0.50	12.60	0.50	4.39
TCI2/TRDVI	0.40	11.99	0.41	11.95	0.41	5.37
TCI3/TRDVI	0.46	13.14	0.47	14.75	0.47	4.67
Corn + Wheat						
MCARI/OSAVI	0.04	12.65	0.03	13.00	0.03	16.10
TCARI/OSAVI	0.19	10.34	0.20	9.28	0.20	13.82
MCARI/TRDVI	0.11	12.05	0.11	12.20	0.11	15.13
TCARI/TRDVI	0.31	9.44	0.34	8.41	0.35	11.36
TCI/TRDVI	0.25	10.49	0.27	9.38	0.27	13.78
TCI1/TRDVI	0.16	11.15	0.17	10.65	0.17	13.85
TCI2/TRDVI	0.20	10.67	0.20	10.30	0.20	15.40
TCI3/TRDVI	0.11	12.05	0.11	12.20	0.11	15.13

IV. CONCLUSION

This study has presented and tested a remote sensing approach for chlorophyll estimation over crop canopies, with minimum effects from the canopy leaf area index (LAI). Based on simulated and measured datasets, we compared several combined indices which are both sensitive to chlorophyll content variations, and relatively resistant to the variations of LAI. The relationships between chlorophyll content and combined optical indices have shown similar trends for both PROSPECT-SAILH simulated data and ground measured datasets, indicating that both spectral measurements and radiative transfer models hold comparable potential for quantitative retrieval of crop foliar pigments. The dataset used showed that crop type had a clear influence on the establishment of predictive equations as well as on their validation. Moreover, corn and wheat data have led to contrasting agreement between estimated and measured chlorophyll contents even for the same predictive algorithm. Indices TCARI/TRDVI and TCI/TRDVI seem to be relatively consistent and more stable as estimators of crop chlorophyll content.

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