

# Exploring the Relationship between Red Edge Parameters and Crop Variables for Precision Agriculture

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**Abstract**—This paper presents the study of the relationships between crop variables and the red edge parameters extracted using the inverted Gaussian model. Variability of the red edge parameters induced by the variations of leaf and canopy model parameters was analyzed using PROSPECT and SAILH simulated spectra. The position and shape of the red edge are influenced mostly by leaf area index (LAI) and chlorophyll content, confounded by the other model parameters. Red edge parameters were also extracted from CASI (Compact Airborne Spectrographic Imager) multi-temporal hyperspectral data, and related with various crop variables. The study shows that red edge parameters are indicative of many crop properties, and the first derivative at the inflection position correlates well with green LAI, crop height and leaf water content. An empirical equation was built from the simulated spectra to predict LAI from the first derivative at the inflection position, and was applied to CASI hyperspectral data for green LAI retrieval. For all the samples including wheat, corn and soybean, comparison between the predicted and measured LAI resulted in a determination coefficient ( $R^2$ ) of 0.86, and an RMSE of 0.61.

**Keywords**—red edge parameters; crop properties; precision agriculture; hyperspectral; inverted Gaussian model

## I. INTRODUCTION

The red edge reflectance has been a focus of research in remote sensing of vegetation, since most of the canopy spectral information is contained in the red and near infrared bands; the position and shape of red edge are indicative of plant chlorophyll content, biomass and plant water content [1]. The accuracy of the red edge parameters estimated is dependent upon sensor bands position and width [2]. Various techniques have been developed for extracting the red edge parameters from different sources of spectral data with minimized estimation error and improved performance. These techniques include the derivative analysis, linear interpolation, polynomial fitting, and the inverted Gaussian modeling. Since there are more than ten channels within the red edge region of CASI hyperspectral data, and the spectral bandwidth of these channels is about 7.5 nm, the inverted Gaussian model was used in this study for red edge parameters extraction [3]. The

objective was to explore the red edge spectral region in order to extract useful crop information for precision agriculture applications. The influence of various leaf and canopy variables on the red edge parameters are assessed based on simulated spectra using coupled PROSPECT leaf and SAILH canopy reflectance models, and then used to analyze and interpret the relationships between different crop properties and the red edge parameters extracted from seasonal CASI hyperspectral image spectra.

## II. MATERIAL AND METHODS

### A. Ground Data Collection

The study area is composed of four agriculture fields located at the former Greenbelt Farm of Agriculture and Agri-Food Canada (45°18'N, 75°45'W). Corn, wheat and soybean were planted in the four fields in 2001. The ground truth sites were chosen to represent different field management patterns and plant growth conditions, and to facilitate the development of remote sensing techniques for precision agriculture applications. Three sites in the soybean field, seven sites in the wheat field and six sites in the two corn fields were selected. Three intensive field campaigns were conducted to coincide with the phenological development stages of the early vegetative (IFC1), active growth (IFC2) and reproductive (IFC3) periods of the growing season. Comprehensive data on crop variables were assembled which included LAI, height, chlorophyll-meter measurements, fresh and dry biomass, as well as water content. Detailed descriptions of the *in-situ* field instrumentation and measurement approaches were previously presented by Pattey *et al.* [4] and Strachan *et al.* [5].

### B. CASI Hyperspectral Data

CASI hyperspectral images were acquired with the hyperspectral mode during each of the intensive field campaigns. The 72 channels covered the visible and near infrared portions of the solar spectrum, with 2 m spatial resolution and 7.5 nm bandwidth. CASI data were processed to absolute ground reflectance by an operational processing procedure.

### C. Simulation of Vegetation Spectra

The PROSPECT leaf model [6] and the SAILH canopy model [7] were used to simulate crop spectra. Inputs to the PROSPECT leaf model include leaf equivalent water thickness  $C_w$  ( $\text{g cm}^{-2}$ ), dry biomass content  $C_m$  ( $\text{g cm}^{-2}$ ), chlorophyll a+b content  $C_{ab}$  ( $\mu\text{g cm}^{-2}$ ) and leaf internal structure parameter  $N$ . Inputs to the SAILH model include soil reflectance  $R_{sl}$ , LAI, leaf angle distribution LAD, solar zenith angle  $\theta_s$ , view angle  $\theta_v$ , relative azimuth angle between view and sun directions  $\phi$ . Leaf  $C_w$  does not have significant effect on the red edge portion of the simulated spectrum, therefore it was given a nominal value of 0.01. Average values of the other leaf model inputs were chosen according to Jacquemoud *et al.* [8]. Solar and view directions were fixed to approximate the actual conditions of CASI data acquisition. A soil spectrum extracted from CASI image data, with a reflectance of 0.2 at 670 nm, was used as a typical soil spectrum. Leaf angle distribution was modeled using an elliptical function described by Kuusk [9]. Table I lists all the parameters used in the simulation. The modal angle  $\theta_m$  (or the angle with the maximum distribution) was varied while the eccentricity parameter was fixed at 0.95.  $\Delta$  in the table specifies the variation ranges of the parameters.

TABLE I. PROSPECT AND SAILH MODEL PARAMETERS

PROSPECT model parameters						
Parameter	Cw (g cm <sup>-2</sup> )	Cm (g cm <sup>-2</sup> )	N	Cab (μg cm <sup>-2</sup> )		
Average	0.01	0.004	1.5	45		
Δ	0	0.002	0.2	15		
SAILH model parameters						
Parameter	LAI	θm	θs	θv	φ	Rsl (670nm)
Average	2	45°	35°	0°	0°	0.2
Δ	1.5	15°	0°	0°	0°	0

### D. The Red Edge Parameters

The red edge reflectance between 670 nm and 780 nm was fitted using the inverted-Gaussian model with four parameters, maximum or shoulder reflectance  $R_s$ , minimum reflectance  $R_0$  corresponding to the maximum chlorophyll absorption in the red bands, its position  $\lambda_0$ , and the Gaussian function deviation parameter  $\sigma$ . With these four parameters, the red edge reflectance at any wavelength  $\lambda$  is represented by [3]:

$$R(\lambda) = R_s - (R_s - R_0) \exp(-(\lambda - \lambda_0)^2 / (2\sigma^2)) \quad (1)$$

The red edge inflection point  $\lambda_p$  is defined as:

$$\lambda_p = \lambda_0 + \sigma \quad (2)$$

The first derivative at the inflection point  $R'(\lambda_p)$  can be written as:

$$R'(\lambda_p) = (R_s - R_0)(\lambda_p - \lambda_0) \exp(-(\lambda_p - \lambda_0)^2 / (2\sigma^2)) / \sigma^2 \quad (3)$$

A linear numeric fitting procedure described by Bonham-Carter [10] was used to extract red edge parameters from vegetation spectrum.

### III. CONTRIBUTION OF LEAF AND CANOPY MODEL PARAMETERS TO REFLECTANCE RED EDGE PARAMETERS

In order to assess the effects of leaf and canopy properties on red edge parameters, a set of spectra were simulated using the PROSPECT and the SAILH models. Leaf parameters  $C_m$ ,  $N$ ,  $C_{ab}$  and canopy parameters LAI and  $\theta_m$  were varied in the following way according to Table I: for a given LAI value of 0.5, 2.0 or 3.5, iteratively assign the average- $\Delta$ , average and average+ $\Delta$  to one of the four parameters,  $C_m$ ,  $N$ ,  $C_{ab}$  and  $\theta_m$ , while fix the other three parameters to the average values. This produced parameter set was used in the coupled models for canopy spectrum simulation. For each of the simulated spectra, red edge parameters were extracted and plotted with respect to LAI (Fig. 1).

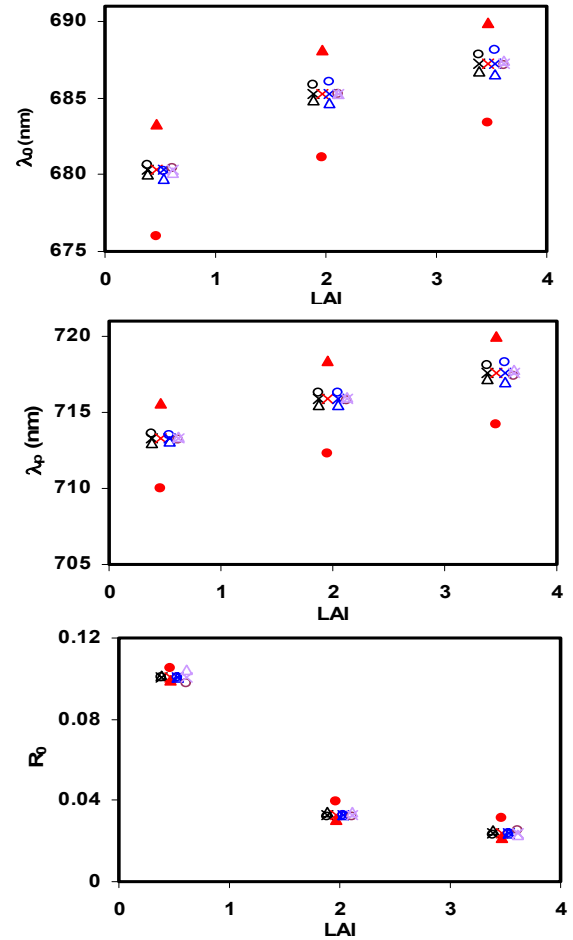


Figure 1. The influence of leaf and canopy parameters on red edge parameters

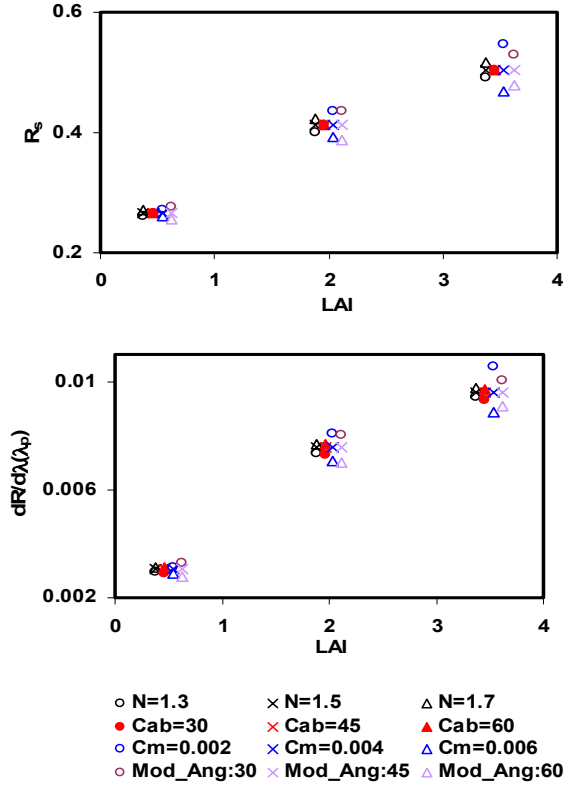


Figure 1 (Continue)

All the varied leaf and canopy model parameters contribute to the variation in the retrieved red edge parameters. It can be observed that, red edge position parameterized by  $\lambda_0$  and  $\lambda_p$  is sensitive to both LAI and leaf chlorophyll content, while relatively insensitive to the other parameters. The red edge moves to longer wavelength when LAI and chlorophyll content increase. The reflectance minimum  $R_0$  decreases with the increase of LAI and then levels off quickly.  $R_0$  is also insensitive to leaf chlorophyll content, due to the strong chlorophyll absorption in the red band. Variability of  $R_0$  induced by the other parameters is negligible.  $C_m$  and  $\theta_m$  have significant influence on the derived shoulder reflectance  $R_s$  and the first derivative  $R'(\lambda_p)$ . When  $C_m$  increases, both  $R_s$  and  $R'(\lambda_p)$  decrease due to the increased absorption by biomass, and for the given illumination and view angle configuration, when  $\theta_m$  increases from  $30^\circ$  to  $60^\circ$ ,  $R_s$  and  $R'(\lambda_p)$  also decrease. Leaf internal structure parameter  $N$  and chlorophyll content have limited effect on  $R_s$  and  $R'(\lambda_p)$ .

#### IV. RELATIONSHIPS BETWEEN CROP PROPERTIES AND RED EDGE PARAMETERS EXTRACTED FROM CASI HYPERSPECTRAL DATA

The relationship between crop properties and the five red edge parameters,  $R_0$ ,  $R_s$ ,  $\lambda_0$ ,  $\lambda_p$ ,  $R'(\lambda_p)$ , extracted from seasonal CASI hyperspectral data were analyzed and summarized in

Table II. In the table, “Green LAI” refers to the LAI of living leaves regardless of their photosynthetic capacity, “leaf water” and “canopy water” refer to leaf and canopy water content per ground area ( $\text{kg m}^{-2}$ ), and SPAD is a measure of leaf chlorophyll content using chlorophyll-meter. The relationships between crop height and red edge parameters were analyzed separately for corn, soybean and wheat, because the typical dynamic ranges of the height of these crops are quite different. The values in Table II are the best determination coefficient  $R^2$  between red edge parameters and crop properties using different regression models: linear, exponential and power models. The red edge parameters are significantly related with crop properties, except that there is no relation between SPAD and shoulder reflectance.

TABLE II. CORRELATION ( $R^2$ ) BETWEEN RED EDGE PARAMETERS (FROM CASI IMAGES) AND CROP BIOPHYSICAL/BIOCHEMICAL PARAMETERS

$R^2$	$\lambda_0$	$\lambda_p$	$R_0$	$R_s$	$R'(\lambda_p)$
SPAD	0.54 <sup>L</sup>	0.24 <sup>L</sup>	0.37 <sup>L</sup>		0.28 <sup>L</sup>
Green LAI	0.87 <sup>E</sup>	0.54 <sup>L</sup>	0.91 <sup>E</sup>	0.74 <sup>L</sup>	0.86 <sup>P</sup>
Leaf Water	0.74 <sup>E</sup>	0.34 <sup>L</sup>	0.72 <sup>E</sup>	0.65 <sup>L</sup>	0.83 <sup>P</sup>
Canopy water	0.80 <sup>E</sup>	0.60 <sup>L</sup>	0.82 <sup>E</sup>	0.48 <sup>L</sup>	0.82 <sup>P</sup>
Height: wheat	0.76 <sup>E</sup>	0.78 <sup>L</sup>	0.80 <sup>P</sup>	0.29 <sup>E</sup>	0.45 <sup>E</sup>
Height: soybean	0.98 <sup>E</sup>	0.72 <sup>L</sup>	0.98 <sup>P</sup>	0.98 <sup>P</sup>	0.99 <sup>E</sup>
Height: corn	0.88 <sup>E</sup>	0.86 <sup>E</sup>	0.84 <sup>P</sup>	0.78 <sup>E</sup>	0.86 <sup>E</sup>

Superscript L, E and P refer to linear, exponential and power regression model, respectively.

Although water absorption in the red edge region was relatively weak, the correlation between water content and the red edge parameters is high. This is possibly because of the secondary effect of water content on the spectral reflectance of leaves, owing to the decreased absorption by pigments [11]. But more importantly, this might be because of the high correlation between water content (mass per ground area) and LAI.

Correlation between crop height and red edge parameters is much stronger for corn and soybean than for wheat. This is because wheat was at the senescent stage at IFC3, when the red reflectance increases and near infrared reflectance decreases significantly, which influenced the red edge parameters. This decisive factor led to a noteworthy low correlation between the height of wheat and  $R_s$  and  $R'(\lambda_p)$ .

The overall correlation between leaf SPAD and red edge parameters is not as high as that of green LAI. This was because inter and intra crop variability of green LAI was much more significant than that of leaf chlorophyll content. There was no relationship between leaf SPAD and  $R_s$  for all crops because there is no pigment absorption beyond the near infrared region.

Green LAI is highly correlated with the red edge parameters. It was also observed from the simulation results that,  $\lambda_0$  is highly sensitive to chlorophyll content,  $R_0$  becomes saturated even for LAI as low as 2, only  $R_s$  and  $R'(\lambda_p)$  are sensitive to LAI with a wide range of LAI. Further analysis shows that, although LAI is better linearly related with  $R_s$ , with a power model, it is much better related with the first derivative  $R'(\lambda_p)$ .

## V. PREDICTION OF GREEN LAI FROM CASI HYPERSENSPECTRAL DATA

Because of the high correlation between green LAI and  $R'(\lambda_p)$ , it is possible to estimate green LAI from the first derivative at the red edge inflection point. A prediction equation was built based on PROSPECT and SAILH simulated spectra. For the simulation, LAI was randomly varied between 0 and 7 with a uniform distribution,  $C_m$ ,  $C_{ab}$ ,  $N$  and  $\theta_m$  were randomly varied between  $\pm\Delta$  from their average values, and the other parameters were kept unchanged (Table I). Red edge parameters were calculated from 150 randomly simulated spectra, and  $R'(\lambda_p)$  was then calculated. A prediction equation was built between input parameter LAI and the calculated  $R'(\lambda_p)$ , and is given in (4). This equation was applied to CASI image spectra for green LAI estimation. For all the samples, including samples from the three IFCs and all the ground truth sites in corn, soybean and wheat fields, the coefficient of determination  $R^2$  between the estimated and measured green LAI is 0.87, with an RMSE of 0.61. Fig. 2 shows the comparison.

$$LAI = 4.4 * (100R'(\lambda_p))^{1.72} \quad (4)$$

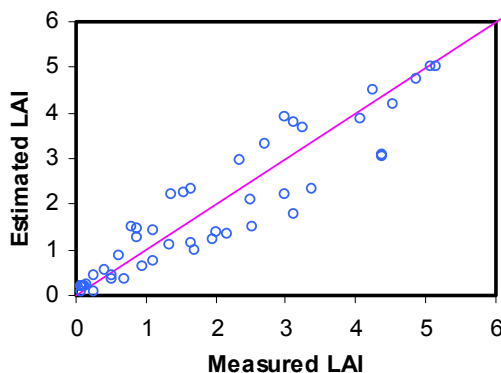


Figure 2. Comparison between the measured and estimated LAI using  $R'(\lambda_p)$

## VI. DISCUSSION AND CONCLUSIONS

The shape and position of the red edge reflectance are well represented by CASI hyperspectral data, with more than ten channels positioned in the red edge region. The inverted Gaussian model can favorably extract not only the position, but also the other parameters that define the shape of the red edge. However, due to its complex structure, the red edge is not easily to be parameterized completely. For instance, the first derivative of red edge reflectance represented by the inverted Gaussian model has only one peak position, but recent studies showed that it actually has a double peak structure, a subtle effect attributed to the additive effect of natural fluorescence emission of chlorophyll a [12]. Still, it can be observed from this study that, red edge parameters extracted using the inverted

Gaussian model are indicative of crop properties such as green LAI, leaf chlorophyll content, leaf and canopy water content, and crop height. Green LAI could be estimated from the first derivative at the red edge inflection point. The results confirmed that red edge position or shape could be used for crop stress monitoring, and even for estimation of crop properties. But, because of the confounding effects between different crop variables on red edge reflectance, special care should be taken when inferring the red edge parameters in terms of crop properties as ambiguities may be unavoidable.

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