

Vegetation Stress Detection through Chlorophyll $a + b$ Estimation and Fluorescence Effects on Hyperspectral Imagery

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ABSTRACT

Physical principles applied to remote sensing data are key to successfully quantifying vegetation physiological condition from the study of the light interaction with the canopy under observation. We used the fluorescence–reflectance–transmittance (FRT) and PROSPECT leaf models to simulate reflectance as a function of leaf biochemical and fluorescence variables. A series of laboratory measurements of spectral reflectance at leaf and canopy levels and a modeling study were conducted, demonstrating that effects of chlorophyll fluorescence (CF) can be detected by remote sensing. The coupled FRT and PROSPECT model enabled CF and chlorophyll $a + b$ (C_{a+b}) content to be estimated by inversion. Laboratory measurements of leaf reflectance (r) and transmittance (t) from leaves with constant C_{a+b} allowed the study of CF effects on specific fluorescence-sensitive indices calculated in the Photosystem I (PS-I) and Photosystem II (PS-II) optical region, such as the curvature index [CUR; $(R_{675}R_{690})/R_{683}^2$]. Dark-adapted and steady-state fluorescence measurements, such as the ratio of variable to maximal fluorescence (F_v/F_m), steady state maximal fluorescence (F'_m), steady state fluorescence (F_s), and the effective quantum yield ($\Delta F/F'_m$) are accurately estimated by inverting the FRT–PROSPECT model. A double peak in the derivative reflectance (DR) was related to increased CF and C_{a+b} concentration. These results were consistent with imagery collected with a compact airborne spectrographic imager (CASI) sensor from sites of sugar maple (*Acer saccharum* Marshall) of high and low stress conditions, showing a double peak on canopy derivative reflectance in the red-edge spectral region. We developed a derivative chlorophyll index (DCI; calculated as D_{705}/D_{722}), a function of the combined effects of CF and C_{a+b} content, and used it to detect vegetation stress.

MOST CURRENT ASSESSMENTS of forest condition are limited to ground-based visual evaluation (e.g., Canadian Forest Service, 1999). Although these conventional field assessments are valuable, they do not reveal physiological changes that characterize early stress responses (Sampson et al., 2000). Assessing physiological condition can indicate productivity and adaptability to environmental stress (Chapin, 1991; Colombo and Parker, 1999) and may provide early indication of decline in stand vigor and productive capacity. Early detection of stress with remote sensing methods could help to identify stress status at larger temporal and spatial scales and before damage is visible. However, to determine vegetation condition from the study of the interaction

between the light and the canopy under observation, physical methods must be developed (Zarco-Tejada, 2000).

The C_{a+b} content is a potential indicator of vegetation stress because of its direct role in the photosynthetic processes of light harvesting and initiation of electron transport and its responsiveness to a range of stresses. In the chloroplast, light energy is harvested and processed by two functional units designated Photosystem I (containing chlorophyll with an absorption peak at 700 nm) and Photosystem II (chlorophyll absorption peak at 680 nm), which produce oxygen and energy through a series of reduction–oxidation reactions to transport electrons. Stressed vegetation can undergo various physiological perturbations in the light-dependent reactions of photosynthesis, including disruption of electron transfer, production of deleterious oxygen derivatives, photobleaching, pigment-bed reorganization, and structural damage to photosynthetic pigments. Differences in remote sensing reflectance between healthy and stressed vegetation due to changes in C_{a+b} levels have been detected previously in the green peak and along the red-edge spectral region (690 to 750 nm) (e.g., Rock et al., 1988; Vogelmann et al., 1993; Carter, 1994; Gitelson and Merzlyak, 1996).

Assessing CF is also a well-established physiological approach to detect previsual strain (Mohammed et al., 1995). Changes in chlorophyll function often precede changes in chlorophyll content, hence CF changes are often observed long before leaves become chlorotic. Chlorophyll fluorescence is red and far-red light produced in photosynthetic tissues upon excitation with natural or artificial light in the visible spectrum. Chlorophyll fluorescence production is one way plant chloroplasts harmlessly dissipate light energy that exceeds photosynthesis requirements, thereby protecting the chloroplasts from light-induced oxidative damage. According to several reviews of CF theory, measurement methods and interpretation (e.g., Papageorgiou, 1975; Krause and Weis, 1984; Schreiber and Bilger, 1987; Lichtenthaler and Rinderle, 1988; Lichtenthaler, 1992; Larcher, 1994; Schreiber et al., 1994), steady state CF and photosynthetic rate are inversely related (i.e., CF is low when photosynthesis is high). In addition, CF techniques

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Abbreviations: CASI, compact airborne spectrographic imager; CF, chlorophyll fluorescence; C_{a+b} , chlorophyll $a + b$; CUR, reflectance curvature index [$(R_{675}R_{690})/R_{683}^2$]; DCI, derivative chlorophyll index; D_x , value of the derivative reflectance at wavelength X in nanometers; FRT, fluorescence–reflectance–transmittance model; F'_m , steady state maximal fluorescence; F_s , steady state fluorescence; F_v/F_m , ratio of variable to maximal fluorescence; $\Delta F/F'_m$, effective quantum yield; PAM, pulse amplitude modulation; PS-I, Photosystem I; PS-II, Photosystem II; RMSE, root mean square error; RT, radiative transfer; R_x , value of the reflectance at wavelength X in nanometers.

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are rapid, nondestructive, and noninvasive (Mohammed et al., 1995).

Evidence of a solar-induced fluorescence signal superimposed on leaf reflectance signatures was first reported by Buschmann and Lichtenthaler (1988) as a result of laboratory studies with a reflection–absorption–fluorescence spectrometer. Other studies of the effect of fluorescence in apparent reflectance have been conducted (Peñuelas et al., 1995; Gamon et al., 1997; Peñuelas et al., 1997, 1998; Gamon and Surfus, 1999; Gitelson et al., 1999), although the effect of the fluorescence signal on the apparent reflectance spectra of leaves has not been quantified.

A study of whether chlorophyll fluorescence is measurable with a passive instrument such as an airborne hyperspectral imager (Zarco-Tejada, 2000) showed that radiative transfer (RT) theory, constrained by appropriate modeling assumptions, can be investigated at leaf, laboratory, and near-field scales to demonstrate that CF effects are detectable as part of leaf reflectance and transmittance, as well as near-canopy reflectance measurements collected over vegetation. Further studies of the theoretical basis for quantitatively estimating pigments by scaling up optical indices have focused on remote sensing methods based on RT and infinite reflectance models (Zarco-Tejada et al., 2000a,b, 2001a,b).

Extensive research performed at the leaf level have demonstrated the use of a large number of optical indices for C_{a+b} estimation, enabling the study of differences in reflectance between healthy and stressed vegetation due to changes in pigment levels (e.g., Rock et al., 1988; Vogelmann et al., 1993; Carter, 1994). Estimating pigment content with optical indices has been shown to produce the best results at leaf and canopy levels with red-edge, spectral, and derivative red-edge indices (Zarco-Tejada et al., 2001b).

Investigation of the effects of fluorescence contributions to the remotely observed signature identified optical indices calculated from leaf reflectance measurements related specifically to fluorescence emission in the 680- to 740-nm spectral region due to PS-II and PS-I (Zarco-Tejada et al., 2000a,b). Indices related to fluorescence maxima at 685 and 735 nm may be useful to study the relationship of leaf and canopy reflectance with chlorophyll fluorescence, such as R_{685}/R_{655} , $R_{683}^2/(R_{675} \cdot R_{691})$, and D_{730}/D_{706} .

These indices were assessed through RT modeling with the FRT simulation model (Zarco-Tejada et al., 2000a), which includes fluorescence flux in the RT differential equations. Here we discuss the results of an assessment of a coupled FRT with the PROSPECT leaf model (Jacquemoud and Baret, 1990) for fluorescence estimation by model inversion. Further, we look at the effects of chlorophyll fluorescence and pigment content on the derivative reflectance, focusing on the understanding of such effects on hyperspectral imagery collected with the airborne CASI instrument.

MATERIALS AND METHODS

Data Collection

In 1998 and 1999, leaf material was sampled from three-year-old potted trees of sugar maple for laboratory–green-

house experiments and from twelve 30- × 30-m sugar maple study sites in the Algoma Region, Ontario, Canada.

The greenhouse experiments required one set of 30 leaves with similar chlorophyll content (49 to 53 units according to SPAD-502 [Minolta Camera Co., Osaka, Japan] chlorophyll meter readings and from subsequent pigment analysis, $\bar{x} = 58.08 \mu\text{g}/\text{cm}^2$, $s = 5.26$, $n = 30$). Leaf samples with similar chlorophyll content were required to study how the apparent leaf reflectance and transmittance vary due to the effects of chlorophyll fluorescence. For the second greenhouse experiment, 60 leaves with variable chlorophyll content ($\bar{x} = 35.66 \mu\text{g}/\text{cm}^2$, $s = 15.87$, $n = 60$) were sampled to study variations in the apparent leaf reflectance and transmittance due to changes in pigment content and chlorophyll fluorescence and were used to estimate pigment by model inversion.

In 1998 and 1999, 440 single leaf samples were collected from the 12 sugar maple study sites. Reflectance and transmittance were measured on these leaf samples with a LI-COR (Lincoln, NE) 1800-12 integrating sphere, coupled by a 200- μm -diameter single mode fiber to an Ocean Optics (Dunedin, FL) Model ST 1000 spectrometer, with a 1024-element detector array, 0.5-nm sampling interval, and approximately 7.3-nm spectral resolution in the 340- to 860-nm range.

Chlorophyll fluorescence variables F_v/F_m , F_i , $\Delta F/F_m$, and F'_m were measured with a pulse amplitude modulation (PAM) fluorometer (PAM-2000; Heinz Walz GmbH, Effeltrich, Germany), which has been used widely in basic and applied fluorescence research (Mohammed et al., 1995). The term F_v/F_m quantifies the maximal efficiency of photon capture by open PS-II reaction centers and is one of the most widely used chlorophyll fluorescence variables. It is calculated from the equation $F_v/F_m = (F_m - F_o)/F_m$, where F_m is the maximal fluorescence yield of a dark-adapted sample, with all PS-II reaction centers fully closed, and F_o is the minimum fluorescence yield of a dark-adapted sample, with all PS-II reaction centers fully open. Effective quantum yield, which denotes the actual efficiency of PS-II photon capture of light by closed PS-II reaction centers, was determined as $\Delta F/F'_m = (F'_m - F_i)/F'_m$, where F'_m is the maximal fluorescence of a pre-illuminated sample with PS-II centers closed, and F_i is the fluorescence at steady state. Procedures used for measuring F_v/F_m and $\Delta F/F'_m$ were based on standard methods (Heinz-Walz-GmbH, 1993). To measure maximal fluorescence induction F_v/F_m , leaves were dark-adapted in bags at room temperature for at least 30 min.

In 1998 and 1999, airborne hyperspectral imagery was collected over the 12 sites of sugar maple where ground-truth samples were collected. The CASI sensor acquired hyperspectral reflectance data at 2-m spatial resolution and 72 spectral channels with 7.5-nm spectral bandwidth. The 12-bit radiometric resolution data collected by CASI were processed to at-sensor radiance with calibration coefficients derived in the laboratory. Simultaneously, a Micro-Tops II sunphotometer (Solar Light Co., Philadelphia, PA) was used to collect aerosol optical depth data at 550 nm so image data could be processed to ground reflectance with the CAM5S atmospheric correction model (O'Neill et al., 1997). Reflectance data were georeferenced with GPS data collected aboard the aircraft. Final registration of the hyperspectral mode imagery was achieved by registration to the CASI high spatial resolution imagery with visual identification of ground-referenced 1-m white targets, which served to accurately identify the location of the sites.

Modeling Chlorophyll Fluorescence and Chlorophyll $a + b$ Estimates at the Leaf Level with the Fluorescence–Reflectance–Transmittance and PROSPECT Models

Chlorophyll fluorescence effects on apparent reflectance were simulated at leaf level to validate the coupled FRT–

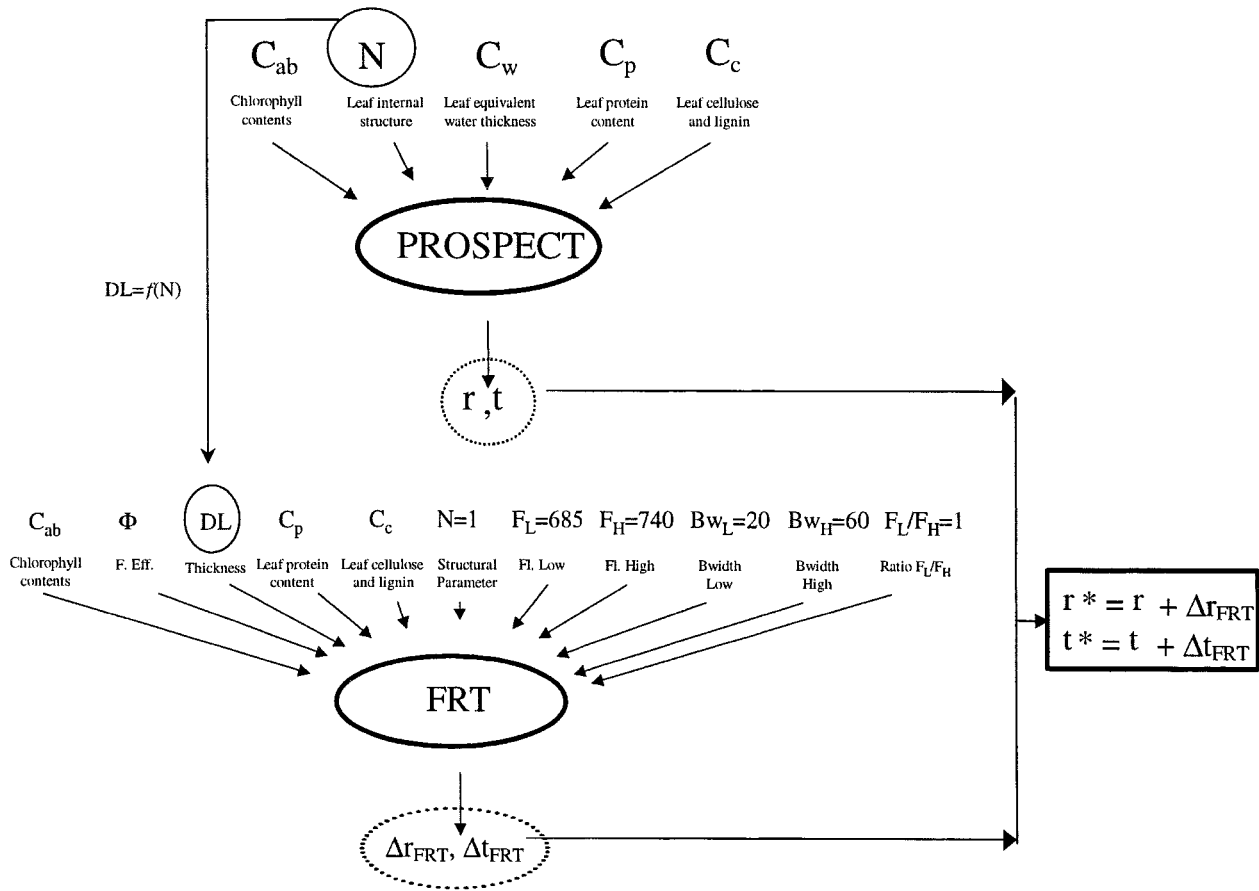


Fig. 1. Schematic diagram showing the coupling between the fluorescence–reflectance–transmittance (FRT) and PROSPECT models to calculate the change in reflectance (r^*) and transmittance (t^*) caused by accounting for chlorophyll fluorescence.

PROSPECT model (Fig. 1). The FRT model coupled to PROSPECT was used to simulate the effects of CF and variable C_{a+b} concentration on the derivative of reflectance to understand spectral features observed from airborne hyperspectral reflectance images collected at 2×2 -m spatial resolution from healthy and stressed sugar maple study sites.

Experimental leaf reflectance, transmittance, pigment content, and chlorophyll fluorescence data were used for assessments through inversion of the coupled model by iterative optimization. The CF effects on leaf reflectance were simulated with the FRT model with input parameters leaf thickness (DL), C_{a+b} content ($\mu\text{g}/\text{cm}^2$), nominal values of protein content (C_p , in g/cm^2), cellulose and lignin content (C_c , in $\mu\text{g}/\text{cm}^2$), and equivalent water thickness (C_w , in cm). The fluorescence signal simulation inputs were the photon fluorescence efficiency (ϕ), ratio f (F_L/F_H) of the fluorescence peak at F_L (P-II center wavelength) relative to that at F_H (P-I center wavelength), and bandwidths B_L and B_H , the full width at half maximum of the fluorescence emissions centered at F_L and F_H wavelengths, respectively.

The coupling method consisted of adding the fluorescence signal modeled by FRT to the leaf reflectance and transmittance spectra simulated by PROSPECT, linking the variables DL (from FRT model) and the structural parameter (N) of the leaf mesophile (dimensionless, from PROSPECT model) through an empirical relationship. The rest of the input parameters needed in FRT for fluorescence modeling (F_L , B_L , F_H , B_H , f , and ϕ) allowed calculation of fluorescence spectra in the 400- to 800-nm range, Δr_{FRT} and Δt_{FRT} , obtaining the final

apparent reflectance (r^*) and transmittance (t^*) as $r^* = r + \Delta r_{FRT}$; $t^* = t + \Delta t_{FRT}$ (Fig. 2).

Canopy reflectance without the effects of fluorescence was simulated with the SAILH canopy reflectance model (Verhoef, 1984) with simulated leaf reflectance and transmittance from PROSPECT.

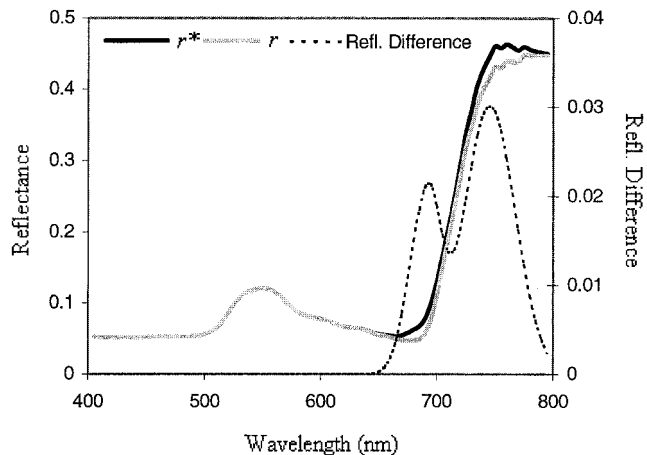


Fig. 2. Fluorescence–reflectance–transmittance (FRT) model simulation of leaf reflectance with the effects of fluorescence flux. Parameters used for the simulation: $\phi = 0.085$, C_{a+b} content = $50 \mu\text{g}/\text{cm}^2$, $DL = 0.075 \text{ mm}$, $F_L = 688 \text{ nm}$, $B_L = 30 \text{ nm}$, $F_H = 746 \text{ nm}$, $B_H = 52 \text{ nm}$, f ratio $F_H/F_L = 0.94$, labeled as r^* (with fluorescence), r (without fluorescence).

The FRT–PROSPECT model for estimating leaf C_{a+b} was assessed with greenhouse experiment data on 60 leaves with variable chlorophyll content and fluorescence. The model was inverted by iterative optimization, varying the structural parameter N from 0.9 to 1.6 to minimize the root mean square error (RMSE) function $\xi(N)$ (Eq. [1]) with both reflectance and transmittance in the near infrared NIR (780–800 nm), where structural effects are dominant in reflectance and transmittance:

$$\text{RMSE} = \xi(N, C_{a+b}) = \sqrt{\frac{\sum_{\lambda} [(r - r_m)_{\lambda}^2 + (t - t_m)_{\lambda}^2]}{n}} \quad [1]$$

where r_m and t_m are reflectance and transmittance measured from the leaf samples with the LI-COR 1800-12 integrating sphere coupled to the fiber spectrometer, and r and t are reflectance and transmittance simulated by the PROSPECT model. In the second step, with N estimated, C_{a+b} was varied from 10 to 70 $\mu\text{g}/\text{cm}^2$ and the function $\xi(N, C_{a+b})$ minimized by calculating the RMSE for the 450- to 700-nm range.

The coupled PROSPECT and FRT model for fluorescence estimation was assessed by looking at the spectral region where CF affects apparent reflectance. The CUR curvature index $[(R_{675}R_{690})/R_{683}^2]$, which was found to correlate strongly with fluorescence (Zarco-Tejada et al., 2000a,b), was used for this assessment. The CUR calculated by the coupled FRT–PROSPECT model in the forward direction was compared with the CUR measured from leaf reflectance samples with variable CF and constant and variable C_{a+b} contents. Input parameters were C_{a+b} measured from the single leaves and N estimated by inverting the PROSPECT model with experimental reflectance and transmittance data. For FRT simulation, inputs were F_L , B_L , F_H , B_H , and fluorescence efficiency ϕ set to 0 (to simulate the CUR without fluorescence effects), and set to PAM-measured variables F_v/F_m , F'_m , and $\Delta F/F'_m$ (to simulate the CUR with fluorescence effects). Steady state fluorescence variables were measured with a halogen light attachment (excitation wavelength < 710 nm) at 110 and 2820 μmol quanta/(m^2 s) to correspond to photosynthetic photon flux densities used to measure reflectance and transmittance with the LI-COR sphere (indicated hereafter as $\Delta F/F'_m110$, F'_m110 , $\Delta F/F'_m2820$).

Detecting Stress by Modeling the Effects of Chlorophyll $a + b$ and Chlorophyll Fluorescence at the Canopy Level with Hyperspectral Data

The effects of chlorophyll fluorescence on apparent reflectance and derivative reflectance were modeled with the FRT–PROSPECT RT model. Simulated fluorescence spectra were modeled with FRT using $\phi = 0.1, 0.15,$ and 0.2 , fluorescence emission centers at 695 nm ($B_L = 30$ nm bandwidth) and 750 nm ($B_H = 40$ nm), leaf structural parameter $N = 1.5$, and $C_{a+b} = 40$ $\mu\text{g}/\text{cm}^2$ (Fig. 3, top left). These were added to leaf reflectance simulated by the PROSPECT model (Fig. 3, top right) and the derivative reflectance with fluorescence (DR*) and without fluorescence (DR) calculated (Fig. 3, middle left). The modeled fluorescence emission superimposed on the simulated reflectance with $C_{a+b} = 40$ $\mu\text{g}/\text{cm}^2$ generated a double peak in the derivative reflectance when ϕ increased (Fig. 3, middle plot, left) due to the effect of the emission bands in the PS-I and PS-II regions. Canopy reflectance without the effects of fluorescence was simulated for different values of pigment content, and its derivative was calculated. Figure 4 shows the simulated canopy reflectance (top) and derivative

reflectance (bottom) with the PROSPECT and SAILH RT models for leaf $C_{a+b} = 40$ and 80 $\mu\text{g}/\text{cm}^2$, $N = 1.5$, canopy leaf area index (LAI) = 6, plagiophile leaf angle distribution function, and nadir view. The derivative reflectance displaces toward longer wavelengths as the pigment content increases. Thus, the derivative chlorophyll index (DCI), calculated as D_{705}/D_{722} , is proposed here to track changes in the double peak generated by the suggested effects of CF and low C_{a+b} content at the canopy level (Fig. 5). Higher values of DCI indicate the presence of such a feature.

RESULTS

Results of the Modeling Methods with the Fluorescence–Reflectance–Transmittance and PROSPECT Models for Chlorophyll Fluorescence and Chlorophyll $a + b$ Estimation at the Leaf Level

Results showed that when chlorophyll content is fixed, the CUR index $[(R_{675}R_{690})/R_{683}^2]$ tracks changes in chlorophyll fluorescence. Relationships between the measured and modeled CUR were $r^2 = 0.72$ (when $\phi = F_v/F_m$), $r^2 = 0.78$ ($\phi = F'_m110$), $r^2 = 0.5$ ($\phi = \Delta F/F'_m110$), and $r^2 = 0.34$ ($\phi = \Delta F/F'_m2820$). No relationship was apparent between the measured and modeled CUR ($r^2 = 0$) when it was modeled with $\phi = 0$, thus the coupled FRT–PROSPECT model simulates fluorescence effects accurately. Varying the emission peak center wavelength in the simulation was found to affect the relationship between the measured and modeled CUR. Better results were obtained with $F_L = 685$ nm than with $F_L = 690$ nm (in both cases $B_L = 20$ nm) as indicated by $r^2 = 0.78$ ($\phi = F'_m110$; $F_L = 685$ nm) (Fig. 6) and $r^2 = 0.68$ ($\phi = F'_m110$; $F_L = 690$ nm). These results demonstrate that the modeled CUR performs well as a reflectance index function of fluorescence emission and that coupling PROSPECT and FRT results in an accurate simulation of the fluorescence effect in apparent reflectance. The best correlation results were obtained by selecting F'_m110 and F_v/F_m as measures of fluorescence efficiency ϕ , with the lack of correlation when $\phi = 0$ demonstrating that the CUR is determined by fluorescence when C_{a+b} content is constant. When both C_{a+b} and CF were variable, the CUR was also affected by changes in C_{a+b} : $r^2 = 0.73$ when the CUR was modeled with $\phi = 0$; $r^2 = 0.85$ ($\phi = F_v/F_m$), and $r^2 = 0.87$ ($\phi = F'_m110$). The C_{a+b} estimation from the set of leaves with variable pigment content achieved $r^2 = 0.96$ and RMSE = 0.02 (Fig. 7) for comparison of estimated and measured C_{a+b} concentration from each leaf. Therefore, the pigment variability within the set of leaf samples used in this study was correctly estimated with the linked FRT–PROSPECT model.

To estimate ϕ , the coupled FRT–PROSPECT model was inverted with reflectance spectra collected in the experiments with constant and variable C_{a+b} and CF. The function minimized was the RMSE between the measured and modeled CUR. Results obtained with constant C_{a+b} allowed modeled fluorescence ϕ estimated by inversion and fluorescence variables measured with PAM (Table 1; Fig. 8) to be compared. These results

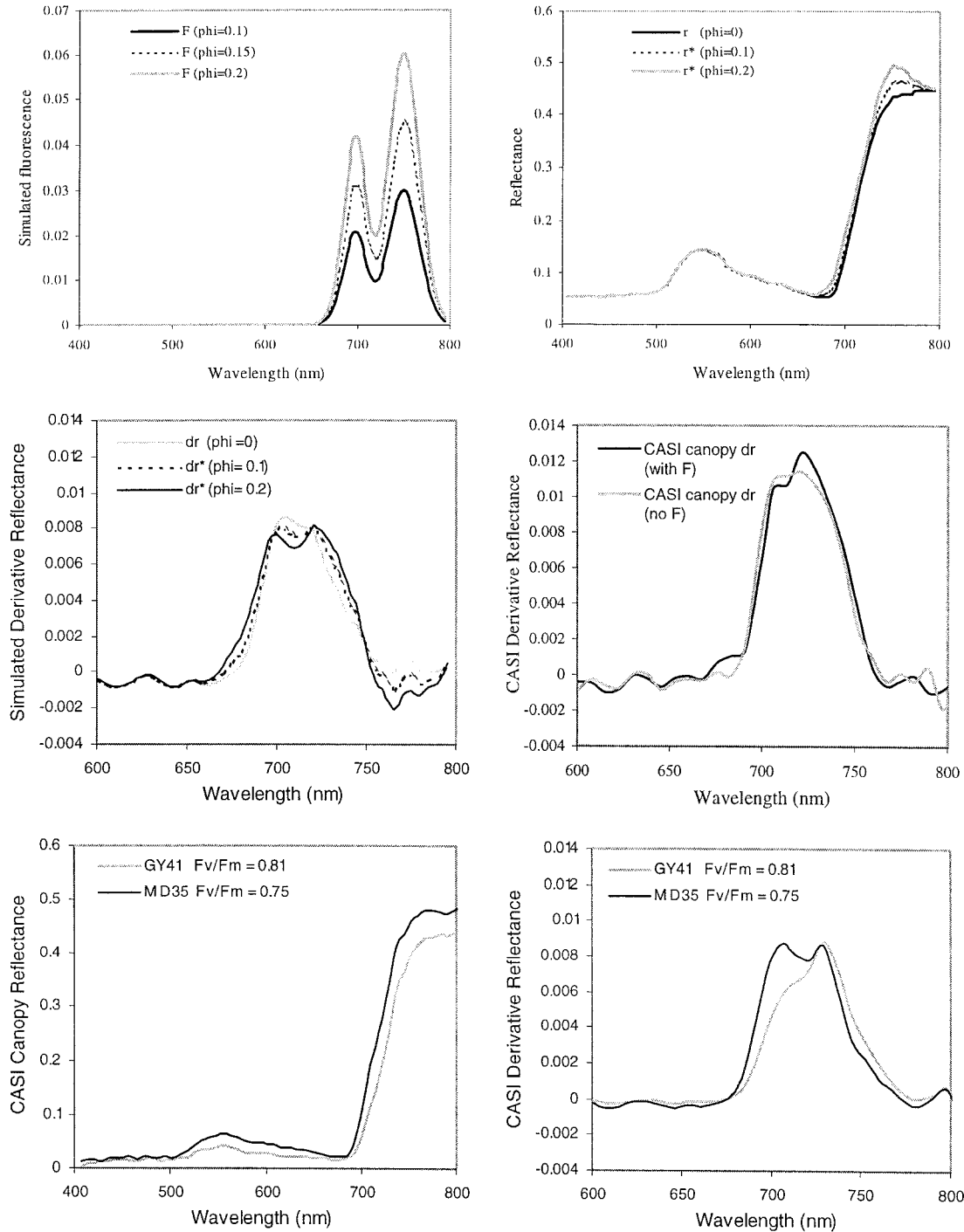


Fig. 3. Simulated leaf reflectance including the effects of fluorescence using the fluorescence–reflectance–transmittance (FRT) model (top and middle left plots) and compact airborne spectrographic imager (CASI) reflectance in the laboratory (middle right plot) and from an airborne campaign (bottom two plots). Top left plot shows simulated fluorescence emission for different values of ϕ (ranging from 0 to 0.2), and superimposed on leaf reflectance (top right plot) with peaks at 695 nm ($B_L = 30$ nm) and 750 nm ($B_H = 40$ nm), $N = 1.5$, and $C_{a+b} = 40 \mu\text{g}/\text{cm}^2$. Derivative reflectance (middle left plot) for different fluorescence simulations shows a double peak as function of fluorescence emission. Laboratory CASI reflectance from sugar maple seedlings with and without fluorescence emission shows that such effects are captured on the derivative reflectance (middle right plot). Airborne CASI data collected over $30 \times 30\text{-m}$ sugar maple study sites (bottom plots) from the two sites with highest field-measured F_v/F_m and C_{a+b} (GY41, $F_v/F_m = 0.81$; $C_{a+b} = 38.8 \mu\text{g}/\text{cm}^2$) and lowest (MD35, $F_v/F_m = 0.75$; $C_{a+b} = 19.08 \mu\text{g}/\text{cm}^2$) show comparable double peak features.

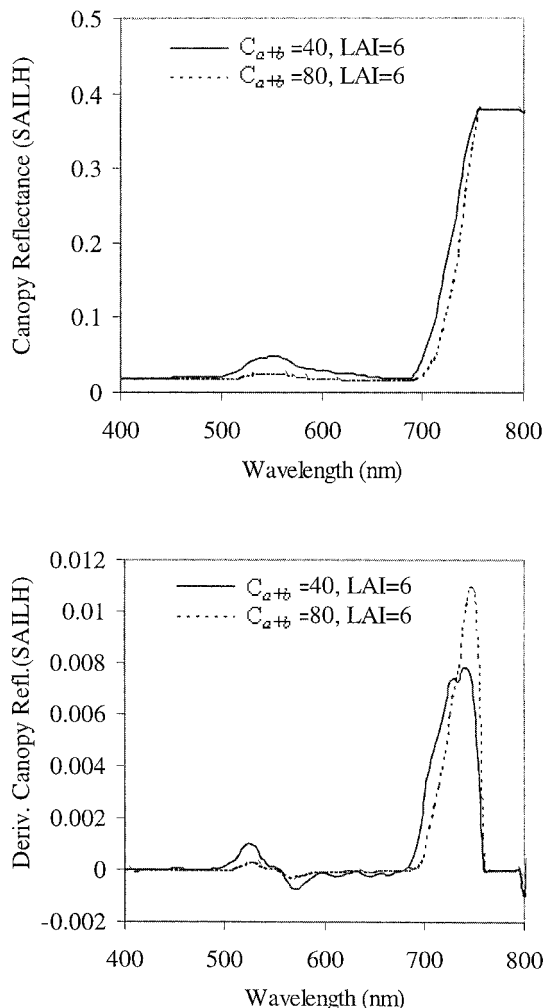


Fig. 4. Simulated canopy reflectance (top) and derivative reflectance (bottom) using the PROSPECT and SAILH radiative transfer models for leaf $C_{a+b} = 40$ and $80 \mu\text{g}/\text{cm}^2$, $N = 1.5$, and canopy leaf area index (LAI) = 6, plagiophile leaf angle distribution function, and nadir view.

with C_{a+b} constant and variable show that inversion of the coupled FRT–PROSPECT model accurately estimates ϕ , thus allowing CF to be estimated from reflectance measurements.

Results at Canopy Level with Hyperspectral Data for Stress Detection

At the canopy level, results showed that the described double-peak effect was found on hyperspectral CASI reflectance images. Airborne imagery was analyzed from the two $20 \times 20\text{-m}$ study areas with highest and lowest stress conditions characterized by C_{a+b} and CF measured in the field. Ground-truth data from the stressed study site reported $C_{a+b} = 19.08 \mu\text{g}/\text{cm}^2$ and $F_v/F_m = 0.75$, while data from the healthy site resulted in $C_{a+b} = 38.8 \mu\text{g}/\text{cm}^2$ and $F_v/F_m = 0.83$.

Hyperspectral reflectance spectra from the healthy and stressed sites (Fig. 3, bottom left, labeled as healthy = GY41 and stressed = MD35) were used to calculate the derivative reflectance (Fig. 3, bottom right)

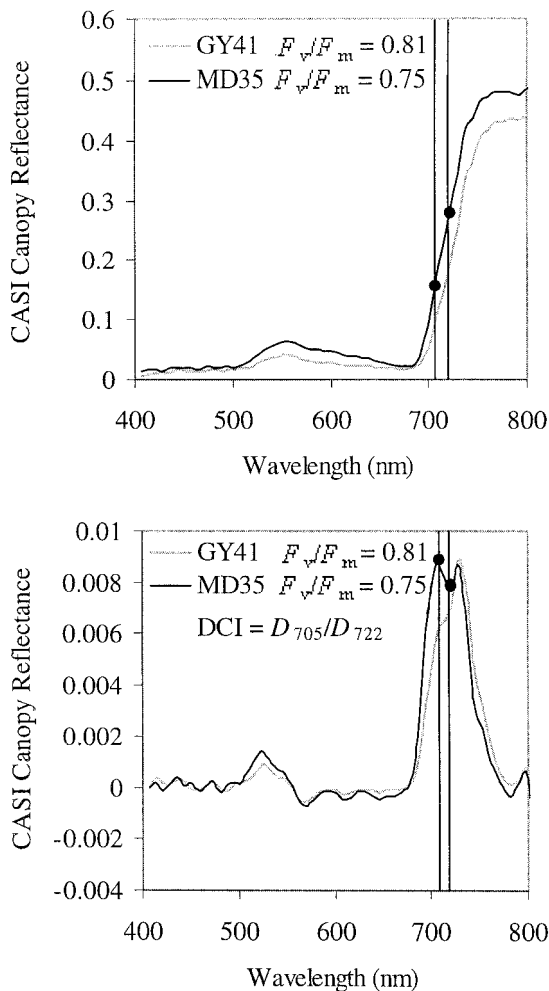


Fig. 5. Band location of the derivative chlorophyll index (DCI) calculated as D_{705}/D_{722} , developed to track changes due to the double peak generated by the suggested effects of pigment and chlorophyll fluorescence at the canopy level in stressed vegetation (healthy site, GY41: $F_v/F_m = 0.81$; $C_{a+b} = 38.8 \mu\text{g}/\text{cm}^2$; stressed site, MD35: $F_v/F_m = 0.75$; $C_{a+b} = 19.08 \mu\text{g}/\text{cm}^2$)

showing the double peak suggested by the combined effects of chlorophyll fluorescence and pigment concentration on stressed vegetation. Results from the laboratory experiment with the CASI sensor collecting data from small canopies with methods for preventing induced CF emission (Fig. 3, middle, right), were consistent with results at the leaf and airborne canopy levels. The plot shows the derivative reflectance collected from the maple canopy in the laboratory with fluorescence emission (after the light source is turned on, therefore exciting fluorescence emission) and after fluorescence emission decreased. Therefore, differences in the derivative reflectance found in this experiment are due to variations in chlorophyll fluorescence tracked at the canopy level with the hyperspectral sensor in the laboratory setting.

These results suggest that hyperspectral reflectance can be used to map stress condition through optical indices calculated on the double-peak red-edge region of the derivative reflectance. The appearance of the

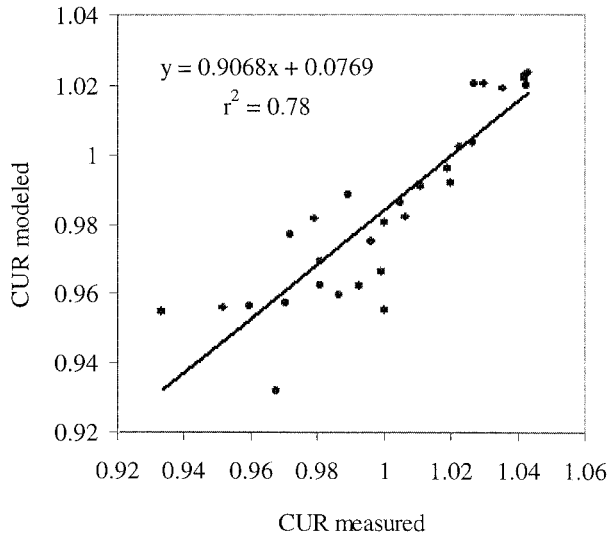


Fig. 6. Relationship between the reflectance curvature index [CUR; $(R_{675} \cdot R_{690})/R_{683}^2$] measured from leaf samples (experiment with C_{a+b} constant) and modeled by fluorescence–reflectance–transmittance (FRT)–PROSPECT. $F_m'_{110}$ was used as input for ϕ in FRT–PROSPECT model.

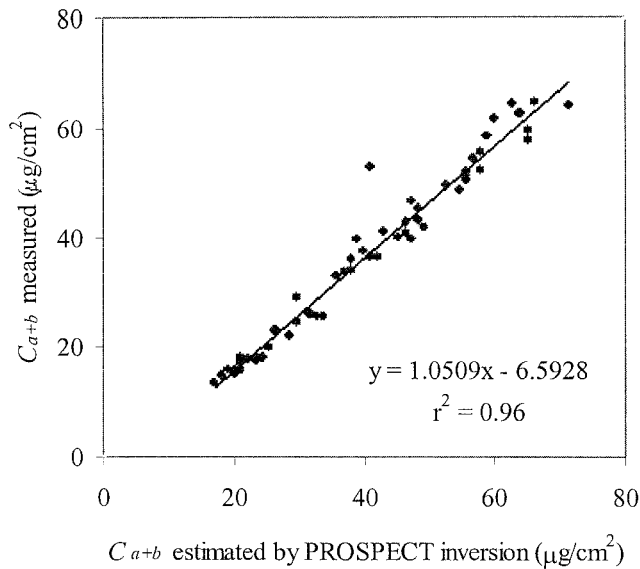


Fig. 7. Estimation of C_{a+b} by inversion of the PROSPECT leaf radiative transfer (RT) model from 60 reflectance and transmittance spectra and C_{a+b} measured from leaves samples with variable chlorophyll content ($\bar{x} = 35.66 \mu\text{g}/\text{cm}^2$, $s = 15.87$, $n = 60$).

double peak could indicate stress conditions due to low pigment content and the existence of CF emission. The severity of the stress would presumably need to be significant or prolonged to exhaust the normal physiological mechanisms that quench CF (thereby reducing its emission) during early stages of stress (Mohammed et al., 1995).

The proposed DCI derivative index was applied to hyperspectral derivative reflectance collected with the CASI sensor over the two study sites with highest and lowest stress conditions (Fig. 9). The 500- × 500-m sugar maple areas showing the 20- × 20-m study sites with lowest field-measured stress (GY41, Fig. 9, top) and

Table 1. Determination coefficients calculated between pulse amplitude modulation (PAM) chlorophyll fluorescence (CF) measurements F_v/F_m , $F_m'_{110}$, $F_m'_{2820}$, F_{110} , F_{2820} , $\Delta F/F_m'_{110}$, and $\Delta F/F_m'_{2820}$ and the estimated ϕ from leaf reflectance data using the fluorescence–reflectance–transmittance (FRT)–PROSPECT model.

	F_v/F_m	$F_m'_{110}$	$F_m'_{2820}$	F_{110}	F_{2820}	$\Delta F/F_m'_{110}$	$\Delta F/F_m'_{2820}$
C_{a+b} constant	0.75	0.75	0.79	0.62	0.77	0.55	0.39
C_{a+b} variable	0.5	0.74	0.66	0.64	0.62	0.62	0.33

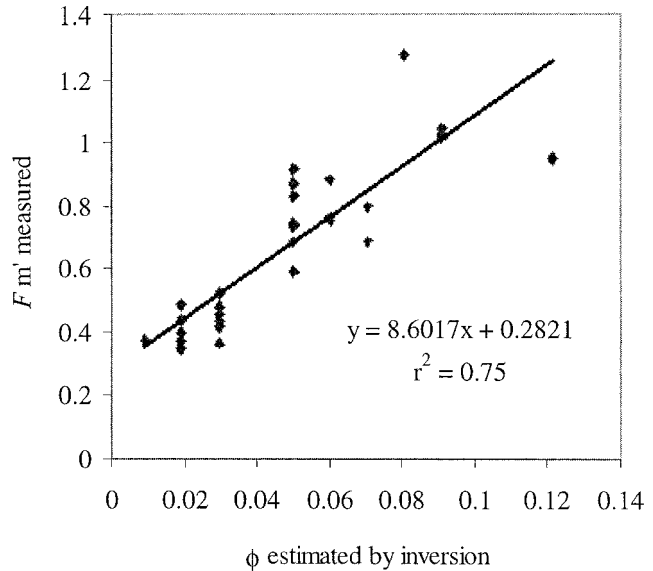


Fig. 8. Relationship between $F_m'_{110}$ measured from leaf samples (experiment with C_{a+b} constant) and ϕ estimated by inversion of fluorescence–reflectance–transmittance (FRT)–PROSPECT.

highest stress (MD35, Fig. 9, bottom) were mapped with DCI reflectance index. Areas of vegetation stress are identified on the 2- × 2-m spatial resolution airborne images in red. Results from the DCI index are consistent with the ground-truth C_{a+b} and F_v/F_m data measured in the field. Coefficients of determination obtained between DCI and F_v/F_m ($r^2 = 0.6$) and between DCI and C_{a+b} ($r^2 = 0.42$) from the airborne hyperspectral imagery collected over the 12 study sites demonstrate the relationship between ground truth measures of stress and the double-peak red-edge DCI reflectance.

SUMMARY

Leaf-level PAM-measured fluorescence variables such as F_v/F_m , F_t , $\Delta F/F_m'$, and F_m' can be estimated from leaf reflectance and transmittance by inverting the coupled FRT and PROSPECT models. Through a set of laboratory experiments with sugar maple leaves, leaf reflectance and transmittance data were collected with a LI-COR integrating sphere attached to a fiber spectrometer, as were CF measurements with a PAM fluorometer. Using the FRT model and experiments with leaf samples with constant and variable C_{a+b} and CF, leaf-level optical indices that can track CF changes through measuring apparent reflectance were validated. Fluorescence-sensitive indices associated with reflectance changes at 690 and 750 nm, such as the curvature

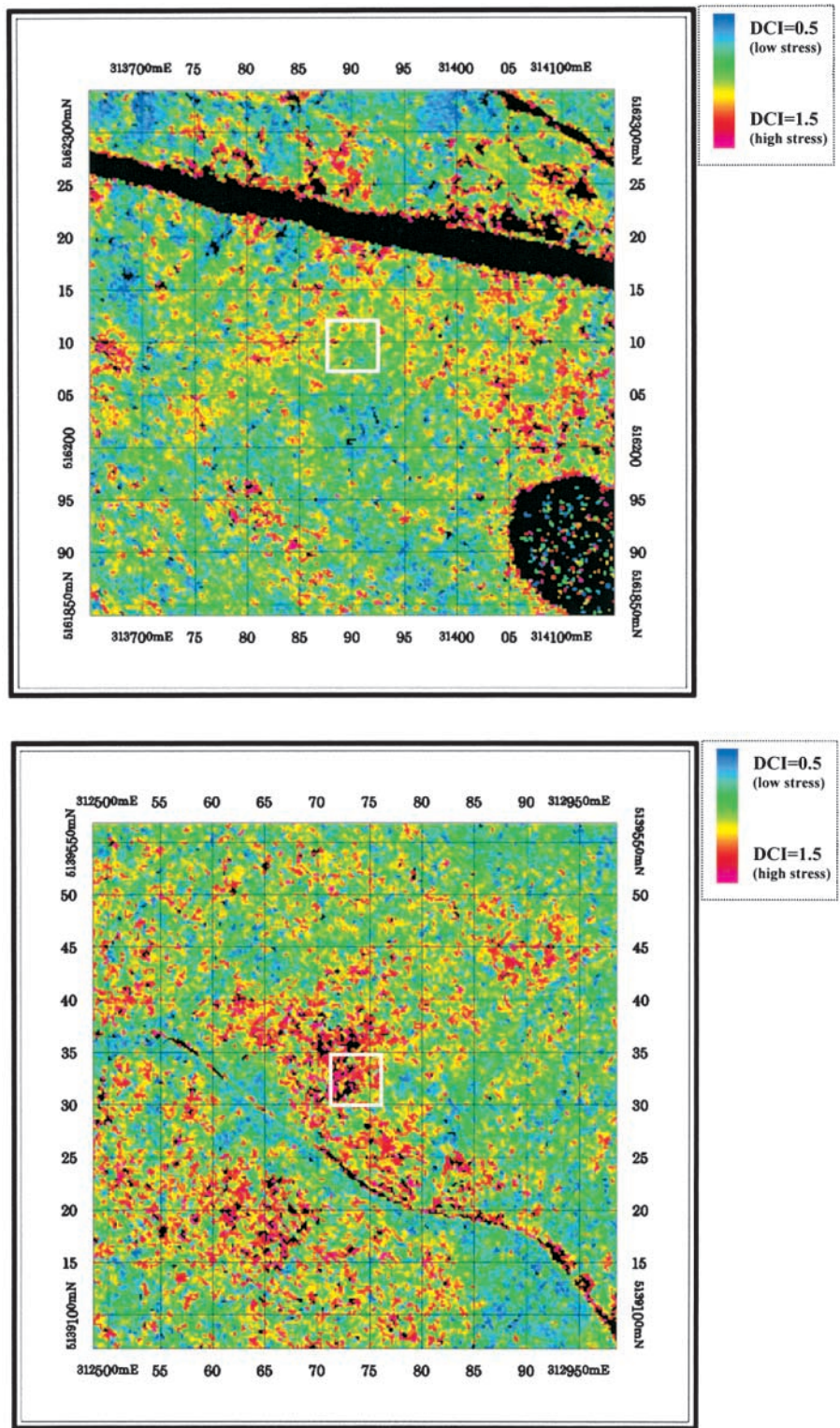


Fig. 9. The derivative chlorophyll index (DCI) applied to hyperspectral derivative reflectance collected with the compact airborne spectrographic imager (CASI) airborne sensor. Remote sensing images were collected over the two study sites with low (top image) and high (bottom image) stress conditions to map the double peak as an indicator of stress. Images show the 500- × 500-m sugar maple areas with the 20- × 20-m study sites with highest field-measured C_{a+b} and F_v/F_m (GY41, $F_v/F_m = 0.81$, $C_{a+b} = 38.8 \mu\text{g}/\text{cm}^2$, top image) and lowest F_v/F_m (MD35, $F_v/F_m = 0.75$, $C_{a+b} = 19.08 \mu\text{g}/\text{cm}^2$, bottom image). Areas of vegetation stress are identified on the 2- × 2-m spatial resolution airborne images in red.

index $(R_{675} \cdot R_{690})/R_{683}^2$, were tested in numerical model inversion through FRT coupled to the PROSPECT leaf model. Inverting FRT-PROSPECT from leaf reflectance and transmittance measurements resulted in accurate estimation ($r^2 = 0.7$) of dark-adapted and steady state fluorescence measures, such as F_v/F_m , F_m' , and F_t . The CF and C_{a+b} effects on the derivative reflectance were modeled showing a double peak in the red-edge region, which is likely due to the combined effects of fluorescence emission and low pigment content on stressed vegetation and is demonstrated by RT modeling. Consistency was found between laboratory time-decay experiments and airborne hyperspectral CASI derivative reflectance collected from two sites of extreme health conditions. The DCI calculated as D_{705}/D_{722} based on the double peak of derivative reflectance is proposed for mapping vegetation stress. The coefficients of determination between the DCI calculated from 12 imaged sites of sugar maple and ground-truth F_v/F_m and C_{a+b} were 0.6 and 0.42, respectively. These results demonstrate the potential of derivative spectroscopy in the red-edge region with hyperspectral remote sensing to map vegetation stress effects.

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