Canopy Optical Indices from Infinite Reflectance and Canopy Reflectance Models for Forest Condition Monitoring: Application to Hyperspectral *CASI* Data

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ABSTRACT

This paper reports on progress made to link physiologically-based indicators to optical indices from hyperspectral remote sensing. This study is carried out on twelve sites of *Acer saccharum* M. in the Algoma Region, Ontario (Canada), where field measurements and hyperspectral *CASI* imagery have been collected in 1997 and 1998 deployments. Individual tree samples were collected at each site for biochemical analysis and measurement of leaf chlorophyll, chlorophyll fluorescence and carotenoid concentrations, as well as leaf reflectance and transmittance. Physiological indices and derivative analysis indices extracted from leaf spectral reflectance have been tested at canopy level using *CASI* data of 72 channels and 2 m spatial resolution at 3 simulation scales which progressively more closely represent the observed above-canopy reflectance spectra from the sites: single leaf reflectance data, infinite reflectance calculated from optically-thick leaf simulation formulae, and canopy reflectance models using nominal site canopy architecture data. This study shows that selected algorithms connecting leaf reflectance and transmittance data to corresponding bioindicators at the leaf level can be expressed at canopy level through canopy models yielding predictions of bioindicators in airborne imaging spectrometer with coefficients of determination as high as 0.91.

1. INTRODUCTION

The aim of the *Bioindicators of Forest Sustainability Project* [1][2] is to develop links between physiologically-based bio-indicators (e.g. pigment concentrations, chlorophyll fluorescence) from field and laboratory data and optical indices from hyperspectral remote sensing for assessing forest condition. This paper reports on results from 12 sites of *Acer saccharum* M. (sugar maple) in the Algoma Region, Ontario (Canada), where field measurements and hyperspectral *CASI* imagery have been collected in 1997 and 1998 field campaigns.

2. DATA COLLECTION

The *CASI* data acquisition was divided into three missions depending on the sensor mode of operation, i.e. *mapping mission*, with 0.5 m spatial resolution and 5 spectral bands; the *hyperspectral mission*, with 2 m spatial resolution, 72 channels and 7.5 nm spectral resolution; and the *full-spectral hyperspectral mission*, with 288 channels and 2.5 nm spectral resolution. Crown cover and LAI measurements were acquired for all the plots using hemispherical photography, a PCA LiCor-2000 and a spherical densiometer. A total of 440 single leaf samples were collected at each site for biochemical analysis and measurement of leaf chlorophyll, chlorophyll fluorescence and carotenoid concentrations. The ratio of variable to maximum chlorophyll fluorescence (Fv/Fm), a measure of photosynthetic efficiency [3], was measured in all leaf samples. Single leaf reflectance and transmittance measurements were acquired on all leaf samples using a Li-Cor 1800 Sphere apparatus with an Ocean Optics fibre spectrometer with 0.5 nm spacing and 7.5 nm spectral resolution in the 400-900 nm range. A *signal-to-noise* study was carried out in order to choose the optimum *passbands* for the smoothing and derivative processing to be applied to the single leaf reflectance and transmittance measurements. It was found that reflectance spectra were optimally smoothed with an order-3 *Savitzky-Golay* algorithm with 25 nm bandwidth; for the calculation of derivative spectra a 13 nm bandwidth was selected using the same *Savitzky-Golay* polynomial fit algorithm.

The 12-bit radiometric resolution data collected by *CASI* was processed to *at-sensor* radiance using calibration coefficients derived in the laboratory by CRESTech. Aerosol optical depth data at 550 nm were collected in the study area at the time of data acquisition in order to process image data to *ground-reflectance* using the CAM5S atmospheric correction model. Reflectance data were afterwards georeferenced using GPS data collected onboard the aircraft. Final registration of the hyperspectral mode imagery was achieved by registration to the mapping mission *CASI* imagery using visual identification of ground-referenced 1 m white targets, which served to identify the location of the sites.

3. SELECTION OF OPTICAL INDICES

Candidate optical indices from reflectance and derivative spectra were identified and grouped into 4 categories, based on the spectral region and the type of parameters used:

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(a) Visible Ratios: SRPI (R_{430}/R_{680}); NPQI (R_{415}-R_{435})/(R_{415}+R_{435}); PRI calculated as (R_{531}-R_{570})/(R_{531}+R_{570}), (R_{550}-R_{531})/(R_{550}+R_{531}) and (R_{570}-R_{539})/(R_{570}+R_{539}); NPCI (R_{680}-R_{430})/(R_{680}+R_{430}); Carter (R_{695}/R_{420}), G (R_{554}/R_{677}) and Lichtenthaler (R_{440}/R_{690}).

(b) Visible/NIR Ratios: NDVI (R_{774}-R_{677})/(R_{774}+R_{677}); SR (R_{774}/R_{677}); Lichtenthaler (R_{800}-R_{680})/(R_{800}+R_{680}), (R_{440}/R_{740}); Gitelson & Merzylak (R_{750}/R_{550}) and SIPI (R_{800}-R_{450})/(R_{800}+R_{650}).

(c) Red Edge Reflectance-Ratio Indices: Vogelmann (R_{740}/R_{720}), (R_{734}-R_{747})/(R_{715}+R_{726}), (R_{734}-R_{747})/(R_{715}+R_{720}); Gitelson & Merzylak (R_{750}/R_{700}); and Carter (R_{695}/R_{760}).

(d) Spectral and Derivative Red Edge Indices: λ_p, λ_o, R_o, R_s and σ from red edge *inverted-gaussian* curve fitting, as well as spectral indices calculated from derivative analysis: (D_{715}/D_{705}); DPR1 ($D_{\lambda o}/D_{\lambda o+12}$), DPR2 ($D_{\lambda o}/D_{\lambda o+22}$), DP21 ($D_{\lambda o}/D_{703}$) and DP22 ($D_{\lambda o}/D_{720}$), amongst others.

The optical indices were calculated at 3 scales which are expected to progressively more closely represent the observed above-canopy reflectance spectra of the sites:

(i) from single leaf reflectance data;
(ii) from infinite reflectance (R_∞) data, calculated by using single leaf reflectance and transmittance data in optically-thick leaf simulation formulae; and
(iii) from canopy reflectance models using single leaf reflectance and transmittance data and nominal canopy architecture data.

In Equations (1) to (3), the optically-thick medium reflectance (denoted the infinite reflectance R_∞) is related to the single leaf reflectance r and the single leaf transmittance t, with single leaf absorptance a calculated as $a = 1 - r - t$, by:

$R_{\infty 1}$ *approx. leaf stack* →
$$\frac{R_\infty}{r} = \frac{1}{1-t^2} \quad (1)$$

$R_{\infty 2}$ *leaf stack* →
$$\frac{R_\infty}{r} = \frac{1}{1-\frac{2t^2}{1+(1-4t^2)^{1/2}}} \quad (2)$$

$R_{\infty 3}$ *thick leaf* →
$$R_\infty = \frac{1-a^{1/2}}{1+a^{1/2}} \quad (3)$$

In Equations (1) and (2) the infinite reflectances ($R_{\infty 1}$, $R_{\infty 2}$) correspond to optically-thick stacks of leaves in which multiple reflectance between leaves is ignored [4], and in which multiple scattering is included (derived using the matrix formulation of Fujimura [5,6]). In Equation (3) the infinite reflectance ($R_{\infty 3}$) characterizes the optically-thick medium with the single-leaf absorption and scattering properties and assumes isotropic scattering [7].

For the application of the *SAIL* [8] and *Kuusk* [9] canopy reflectance models nominal input parameters derived from the study areas were used: LAI=3.5, plagiophile leaf angle distribution function (LADF), soil reflectance data derived from imagery and model-estimated skylight irradiance fraction based on conditions during airborne acquisitions. Additional parameters needed in the *Kuusk* model were n=1.4, sl=0.007 & θ^*=40°, and ε=0.95 & θ_m=45° for the LADF for the assumed plagiophile leaf distribution function.

4. RESULTS OF THE SIMULATION STUDY

Results obtained at leaf level from measurements collected in June and July 1998 demonstrated that a link exists between leaf pigments, chlorophyll-*a*, chlorophyll-*a*&*b*, carotenoids, leaf fluorescence and certain indices. The most promising indices at the individual leaf level are those listed in Table 1, along with their determination coefficients. Using single leaf reflectance and transmittance data as input, the same optical indices were calculated from R_∞ spectra from (1,2,3) and through the SAIL and *Kuusk* canopy reflectance models. These simulated above-canopy optical indices and the corresponding measurements of bioindicators (pigments and fluorescence) from the 440 leaf samples permitted the derivation of prediction algorithms for site bioindicators.

Table 1. Determination coefficients (r>0.6) obtained in the statistical analysis between chlorophyll-*a*, chlorophyll a&*b*, carotenoids and Fv/Fm, and optical indices obtained from *Acer saccharum* M. leaf reflectance and transmittance measurements.

Optical Index	*r chl-a/ cm²*	*r a&b/ cm²*	*r caro/ cm²*	*r ChFl Fv/Fm*
Vogelmann (R_{740}/R_{720})	0.82	0.8	0.8	0.69
PRI (R_{531}-R_{570})/(R_{531}+R_{570})	-	-	-	0.72
PRI (R_{550}-R_{531})/(R_{550}+R_{531})	-0.61	-0.63	-	-0.68
PRI (R_{570}-R_{539})/(R_{570}+R_{539})	-	-	-	-0.68
Carter (R_{695}/R_{760})	-0.77	-0.75	-0.74	-0.64
Gitelson & Merzylak (R_{750}/R_{700})	0.82	0.8	0.8	0.66
Vogelmann (R_{734}-R_{747})/(R_{715}+R_{726})	-0.82	-0.81	-0.81	-0.66
Vogelmann (R_{734}-R_{747})/(R_{715}+R_{720})	-0.83	-0.81	-0.81	-0.66
Lichtenthaler (R_{440}/R_{690})	0.74	0.73	0.74	0.61
λp	0.81	0.79	0.79	0.69
DP22 ($D_{\lambda o}/D_{720}$)	-0.73	-0.72	-0.68	-0.71
Vogelmann (D_{715}/D_{705})	0.82	0.79	0.79	0.69
DP21 ($D_{\lambda o}/D_{703}$)	0.82	0.79	0.79	0.65
Gitelson & Merzylak (R_{750}/R_{550})	0.81	0.79	0.76	-
G (R_{554}/R_{677})	-0.74	-0.72	-0.71	-

5. APPLICATION TO *CASI* DATA

CASI data were collected over the study sites within the same period of the field data acquisition. Mean reflectance values per plot were calculated in each *Acer saccharum* M. study site of 20 x 20 m. Data were acquired in the hyperspectral reflectance mode, with 2 m spatial resolution and 72 spectral channels. The mean reflectance per plot was calculated selecting the brightest 25% pixels in the NIR, therefore targeting crowns while minimizing influence of shadows, canopy openings and the direct understorey reflectance.

Table 2 shows the determination coefficients between measured and the estimated values of chlorophyll-*a*, chlorophyll-*a*&*b*, carotenoids and leaf fluorescence Fv/Fm derived by applying leaf simulation relationships obtained through R_∞ models and *SAIL* and *Kuusk* canopy reflectance models to *CASI* data collected over *Acer saccharum* M. study sites. Figure 1 shows the estimation of Fv/Fm from a Vogelmann optical index R_{740}/R_{720} [10] using $R_{\infty 1}$, $R_{\infty 2}$ and $R_{\infty 3}$, and the *SAIL* and *Kuusk* CR models. It can be seen that the estimation improves when SAIL and *Kuusk* CR models are used. For all indices used the estimations improve (correlation slope progressively approaches unity) when the optical indices are calculated using first R_∞ and then canopy reflectance (CR) models. Figure 2 shows the excellent simulations with the *Kuusk* CR model (i.e. slope=0.99) when the index DP21 ($D_{\lambda o}/D_{703}$) is used to estimate Fv/Fm.

Table 2.- Determination coefficients (r>0.4) obtained in chlorophyll-*a*, chlorophyll a&*b*, carotenoids and Fv/Fm estimations applying relationships from $R_{\infty 1}$, $R_{\infty 2}$, and $R_{\infty 3}$ optically-thick leaf simulation models and *SAIL* and *Kuusk* CR models to *CASI* data collected over *Acer saccharum* M. study sites.

Optical Index	*r chl-a/ cm²*	*r a&b/ cm²*	*r caro/ cm²*	*r ChFl Fv/Fm*
DP21 ($D_{\lambda o}/D_{703}$)	0.64	0.63	0.42	0.91
Vogelmann (R_{740}/R_{720})	0.6	0.6	-	0.9
Vogelmann ($(R_{734}R_{747})/(R_{715}+R_{726})$)	0.61	0.6	-	0.87
Vogelmann ($(R_{734}R\text{-}_{747})/(R_{715}+R_{720})$)	0.61	0.61	-	0.87
Gitelson & Merzylak (R_{750}/R_{700})	0.45	0.44	-	0.84
Carter (R_{695}/R_{760})	-	-	-	0.83
λ_p	0.56	0.56	-	0.82
Vogelmann (D_{715}/D_{705})	0.46	0.45	0.42	0.79
DPR2 ($D_{\lambda o}/D_{\lambda o+22}$),	-	-	-	-0.68
Gitelson & Merzylak (R_{750}/R_{550})	0.45	0.44	-	0.67
DP22 ($D_{\lambda o}/D_{720}$)	-0.55	-0.54	-	-0.63
PRI ($(R_{570}-R_{539})/(R_{570}+R_{539})$)	-	-	-	0.63
DPR1 ($D_{\lambda o}/D_{\lambda o+12}$)	-	-	-	-0.6
PRI ($(R_{531}-R_{570})/(R_{531}+R_{570})$)	-	-	-	0.59
PRI ($(R_{550}-R_{531})/(R_{550}+R_{531})$)	0.59	0.58	-	-
Lichtenthaler (R_{440}/R_{690})	0.46	0.46	-	-
Carter (R_{695}/R_{420})	0.46	0.47	-	-
G (R_{554}/R_{677})	0.46	0.44	-	-

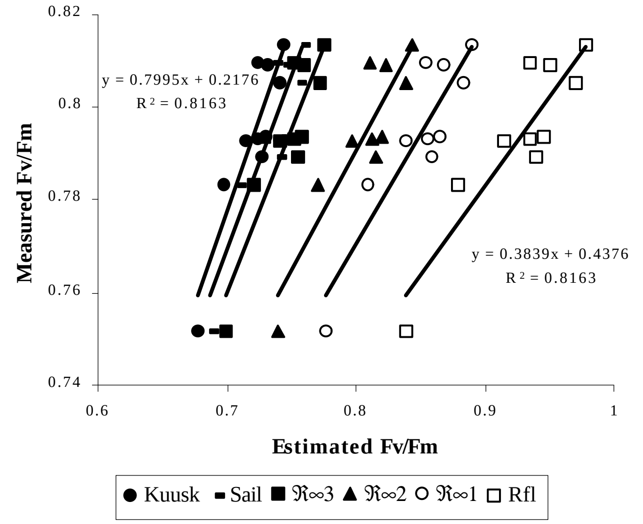

Figure 1.- Estimation of Fv/Fm from *CASI* data using the Vogelmann (R_{740}/R_{720}) algorithm developed at leaf level through R_∞ and CR leaf simulation models. The data corresponds to *Acer saccharum* M. study sites.

An overview of the complete analysis methodology followed in this study is shown in Figure 3. Validation of algorithms in different study sites as well as selective field data acquisition of leaf samples based on the estimations made by optical indices has been planned for the 1999 deployment. An evaluation of the predicative capability of the algorithms and methodology is planned through re-visits of the sites with 1999 field and airborne deployments.

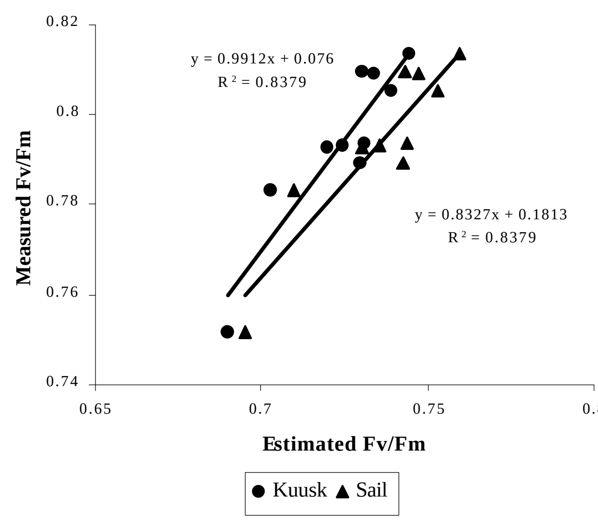

Figure 2.- Estimation of Fv/Fm from *CASI* data using the DP21 ($D_{\lambda o}/D_{703}$) algorithm developed at leaf level through *SAIL* and *Kuusk* CR models. Data from *Acer saccharum* M. study sites.

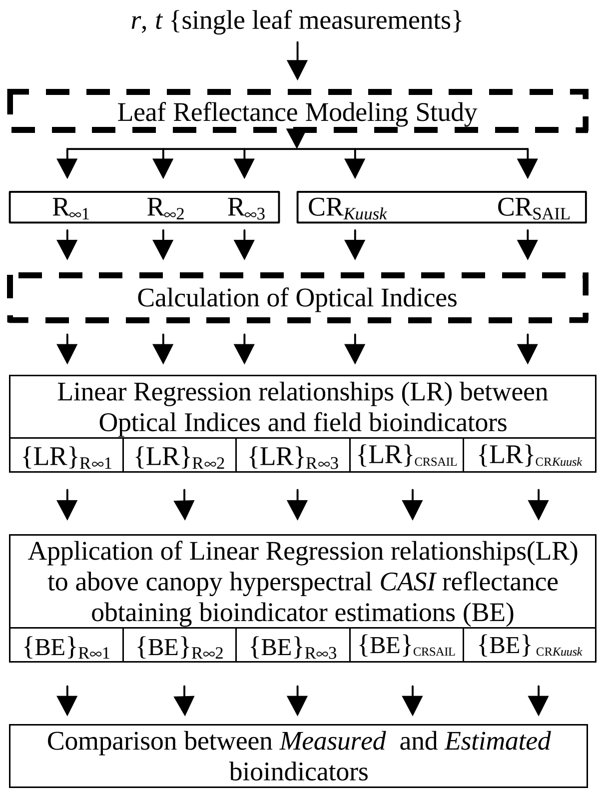

Figure 3. Schematic view of the overall analysis methodology followed in this study.

6. CONCLUSIONS

This study demonstrates a link between physiologically-based indicators and optical indices from hyperspectral remote sensing for *Acer saccharum* M. study sites, as in previous studies. However, these results further suggest that leaf-level measurements of pigments and fluorescence along with leaf reflectance and transmittance can be used to produce algorithms to estimate these variables from above-canopy spectral reflectance. The studies at three scales which progressively more closely represent the observed above-canopy reflectance spectra from the sites, show improvements in the estimation of leaf-based physiological indicators, such as chlorophyll-*a*, chlorophyll-*a&b*, carotenoids and Fv/Fm chlorophyll fluorescence. Canopy structure was shown to play an important role in this link, with *SAIL* and *Kuusk* models improving, in almost all cases, the estimation of the physiologically-based indicators, over the simpler optically-thick leaf simulations.

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