Optical Indices as Bioindicators of Forest Condition from Hyperspectral CASI data

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ABSTRACT: This paper reports on progress made to link physiologically-based indicators to optical indices scaling-up from leaf level to the canopy through *SAIL* and *Kuusk* Canopy Reflectance Models (CR). Hyperspectral CASI data of 2m spatial resolution, 7.5 nm spectral resolution and 72 channels were collected in 1997 and 1998 deployments over twelve sites of *Acer saccharum* M. in the Algoma Region, Ontario (Canada). A field sampling campaign was carried out for biochemical analysis of leaf chlorophyll and carotenoid concentrations, and fluorescence along with leaf reflectance and transmittance. Leaf-level relationships obtained between optical indices and biochemical indicators were scaled-up to canopy level through CR models using input model parameters related to the canopy structure and viewing geometry at the time of data acquisition. The result is an algorithm which predicts leaf-level bioindicators from airborne hyperspectral imagery. A modeling study was carried out to determine the influence of CR parameters such as the Leaf Angle Distribution Function (LADF), LAI and the viewing geometry on the four types of optical indices used in this study: Visible Ratios, Visible/NIR Ratios, Red Edge Reflectance-Ratio Indices, and Spectral and Derivative Red Edge Indices. Nominal CR model parameters appear to be sufficient to allow accurate application of the optical index/bioindicator algorithm to airborne data.

1 INTRODUCTION

The *Bioindicators of Forest Sustainability Project* (Mohammed *et al*., 1997; Sampson *et al*., 1998) aims 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 data for assessing forest condition. This paper reports on results obtained 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. Previous work (Zarco-Tejada *et al.*,1999) shows that optical indices calculated at three scales progressively more closely represented the observed above-canopy reflectance spectra: from single leaf reflectance data; infinite reflectance data, calculated by using single leaf reflectance and transmittance data in optically-thick simulation formulae; and from canopy reflectance models using single leaf reflectance and transmittance data and nominal canopy architecture data. Input CR parameters defining the canopy structure and the viewing geometry at the time of data acquisition are studied in this paper through the *SAIL* CR model in order to study their influence in calculated optical indices.

2 AIRBORNE AND FIELD DATA COLLECTION AND PROCESSING

Crown cover and LAI measurements were acquired for all the plots using hemispherical photography, a PCA Li-Cor 2000 and a spherical densiometer. A total of 440 single leaf samples were collected at 12 *Acer saccharum* M. sites for biochemical analysis and measurement of leaf chlorophyll, carotenoid concentrations and fluorescence. The ratio of variable to maximum chlorophyll fluorescence (Fv/Fm), a measure of photosynthetic efficiency (Mohammed *et al*., 1995), 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 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

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reflectance spectra were optimally smoothed with an order-3 Savitzky-Golay algorithm (Savitzky & Golay, 1964) 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 above-canopy data acquisition using the *CASI* sensor was divided into three missions each with a specific sensor mode of operation: the *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. 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 (O'Neill *et al.*,1997). Reflectance data were 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 accurately identify the location of the sites.

3 SELECTION OF OPTICAL INDICES

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

(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 $(R_{800}-R_{680})/(R_{800}+R_{680})$, and (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 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.

4 *SAIL* AND *KUUSK* CANOPY REFLECTANCE MODELS: LEAF-LEVEL MEASUREMENTS SCALED-UP TO ABOVE-CANOPY LEVEL

The single leaf reflectance and transmittance data collected from the ground-truth deployment were scaled-up to above-canopy level through *SAIL* (Verhoef, 1984) and *Kuusk* (Kuusk, 1996) canopy reflectance models. Optical indices calculated from the simulated above-canopy reflectance were therefore a function of the canopy structure and viewing geometry. Simulated above-canopy optical indices and the corresponding measurements of bioindicators (pigments and fluorescence) from the 440 leaf samples permitted the derivation of

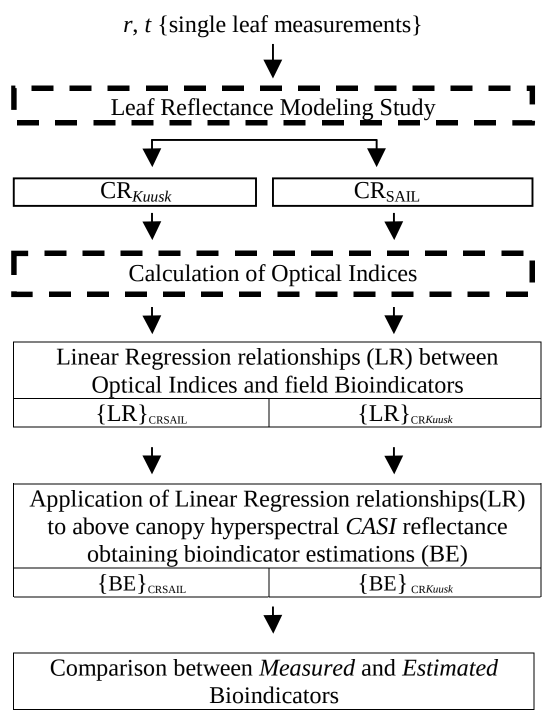

Figure 1. Schematic view of the overall analysis methodology followed in this study. Leaf-level reflectance and transmittance measurements are scaled-up to canopy level through CR models and input parameters related to the canopy structure and viewing geometry. Linear regression Relationships (LR) between optical indices calculated from above-canopy simulated reflectance and ground-truth bioindicators are applied to above-canopy hyperspectral CASI reflectance to obtain bioindicator estimation (BE). Assessment is made comparing ground-truth measured with estimated bioindicators.

prediction algorithms for site bioindicators to be tested on data acquired over the study sites by the hyperspectral *CASI* sensor.

For the application of the *SAIL* and *Kuusk* canopy reflectance models nominal input parameters derived from the study areas were: LAI = 3.5, plagiophile leaf angle distribution function (LADF), soil reflectance data derived from CASI 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 & $\theta_m = 45°$ for the LADF for the assumed plagiophile leaf distribution function.

The schematic view of the simulation study is shown in Figure 1. Single leaf reflectance and transmittance measurements from the field data sampling were used for the simulation of above-canopy reflectance through infinite reflectance and canopy reflectance models *SAIL* and *Kuusk*. Optical indices calculated from above-canopy simulated-reflectance were used to derive linear relationships that are then applied to hyperspectral *CASI* data to obtain bioindicator estimations. Assessment is made comparing *in-field* measured bioindicators with *CASI*-derived estimations.

5 RESULTS AT CANOPY LEVEL FROM HYPERSPECTRAL CASI DATA

CASI data were collected over the study sites within the same period as the field data acquisition. Mean reflectance values per plot were calculated in each *Acer saccharum* M. study site of 20 x 20 m. Data

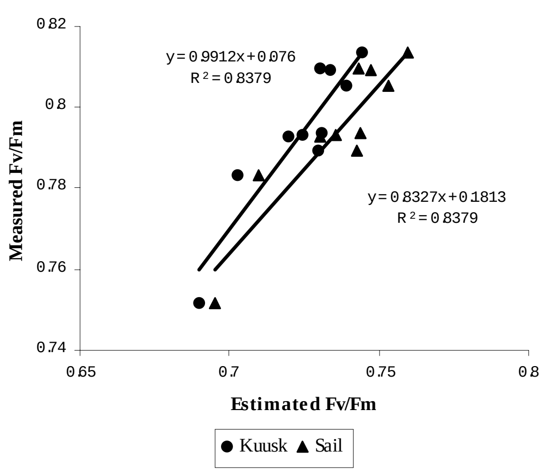

Figure 2. Estimation of Fv/Fm from CASI data using the DP21 ($D_{\lambda o}/D_{703}$) algorithm developed at leaf level through SAIL and Kuusk CR models. Data from *Acer saccharum* M. study sites.

Table 1. Determination coefficients (r > 0.4) obtained in chlorophyll-*a*, chlorophyll a&*b*, carotenoids and Fv/Fm estimations applying relationships from *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_{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	-	-

were acquired in the hyperspectral reflectance mode, with 2 m spatial resolution and 72 spectral channels with 7.5 nm spectral resolution. The mean reflectance per plot was calculated selecting the brightest 25% of pixels in the NIR, therefore targeting crowns while minimizing influence of shadows and canopy openings.

Table 1 shows the determination coefficients between measured and estimated values of chlorophyll-*a*, chlorophyll-*a*&*b*, carotenoids and leaf fluorescence Fv/Fm derived by applying leaf simulation relationships obtained through *SAIL* and *Kuusk* canopy reflectance models to *CASI* data collected over the 12 *Acer saccharum* M. study sites. As an example, the simulations with the *SAIL* and *Kuusk* CR models when the index DP21 ($D_{\lambda o}/D_{703}$) is used to estimate Fv/Fm is shown in Figure 2. The slope near unity (0.99) indicates the effectiveness of scaling up from leaf-level to canopy level.

6 MODEL PARAMETER SENSITIVITY STUDY

For monitoring of bioindicators by remote sensing changes are expected in θ_s during data acquisition in diurnal and seasonal cycles. LAI variations occur with changes in the canopy conditions, as well as changes in LADF between species. A modeling study was carried out in order to determine the influence of changes in the CR parameters on the calculated optical indices and therefore in the final bioindicator prediction. *SAIL* input parameters were changed to study their sensitivity on the indices derived from the simulated canopy spectra. LAI was stepped from LAI = 1 to LAI = 8; LADF was changed to simulate 4 different canopy types: planophile ($\theta = 0°$, $\varepsilon = 0.985$), erectophile ($\theta = 90°$, $\varepsilon = 0.985$), plagiophile ($\theta = 45°$, $\varepsilon = 0.95$), and spherical ($\varepsilon = 0$). Solar zenith angle θ_s was stepped from $\theta_s = 20°$ to $\theta_s = 60°$. Two single leaf measurements of reflectance and transmittance collected as part of the experiment were used for the modeling study. The two leaves used in the study were chosen from the 2 study sites that showed highest and lowest Fv/Fm and Chl_a/cm^2 values in the field: Fv/Fm = 0.69 and $Chl_a/cm^2 = 17.31$ for the high stressed leaf, and Fv/Fm = 0.83 and $Chl_a/cm^2 = 32.2$ for the low stressed or healthy leaf. The modeling study consisted of the comparison of the predicted bioindicator from optical indices through the *SAIL* CR model with nominal CR parameters relative to the prediction when non-nominal CR parameters are used.

Representative optical indices were selected from the 4 categories used in the modeling study: PRI $(R_{531}-R_{570})/(R_{531}+R_{570})$ and Lichtenthaler (R_{440}/R_{690}) from the Visible Ratios optical indices; Gitelson & Merzylak (R_{750}/R_{550}) and NDVI $(R_{774}-R_{677})/(R_{774}+R_{677})$ from the Visible/NIR ratios; Carter (R_{695}/R_{760}), Vogelmann (R_{740}/R_{720}), Vogelmann $(R_{734}-R_{747})/(R_{715}+R_{726})$ and Gitelson & Merzylak (R_{750}/R_{700}) from the Red Edge Reflectance-Ratio Indices; and DP21 $(D_{\lambda o}/D_{703})$, λ_p and Vogelmann (D_{715}/D_{705}) from the Spectral and Derivative Red Edge Indices. At low LAI (< 2) the errors in the predicted bioindicator become large regardless of the type of canopy considered. Figure 3 (top) shows this result using the R_{750}/R_{700} optical index (Gitelson & Merzylak, 1997) for $\theta_s = 30°$ as a function of canopy type and LAI. For values of LAI higher than 3 the differences between the predicted bioindicator using nominal canopy parameters and the prediction with changed θ_s and LADF canopy parameters is insignificant. Moreover, when the LAI is higher than 3 and the θ_s is a nominal 30° the type of canopy is irrelevant for the bioindicator prediction (Figure 3, top).

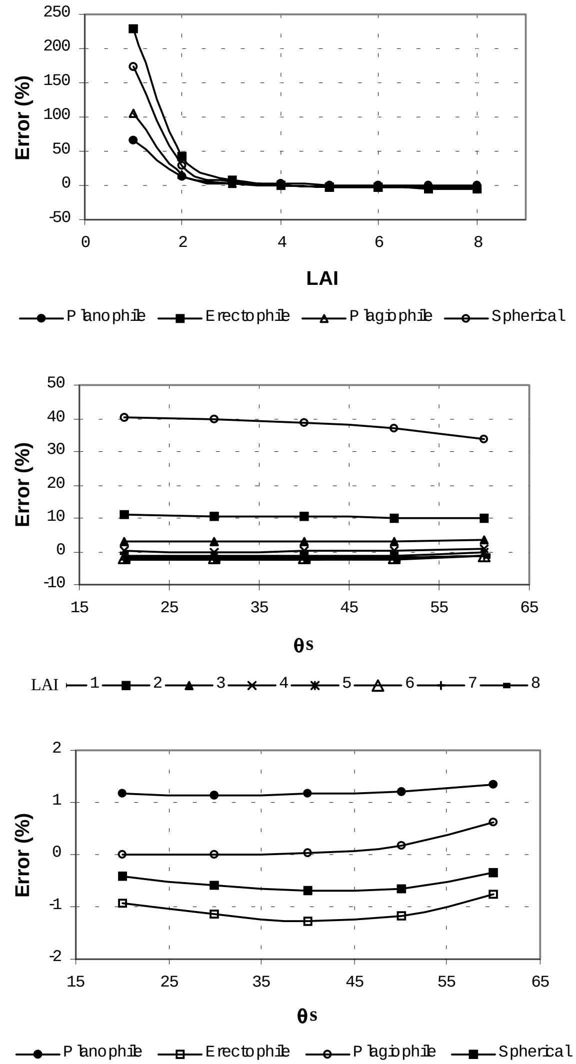

Figure 3. Model parameter sensitivity study shows that low LAI affects bioindicator estimation regardless the type of canopy (top plot, Gitelson & Merzylak index (R_{750}/R_{700}), $\theta s = 30°$) and θs angle (middle plot, Vogelmann index (R_{740}/R_{720}), plagiophile canopy). When $\theta s = 30°$ and LAI > 3 the canopy type is irrelevant (top plot). θs has no effect in the bioindicator estimation as can be seen in the middle plot (LAI ranging from 1 to 8) and bottom plot (DP21 index $(D_{\lambda o}/D_{703})$, LAI = 4) for any type of canopy. The % Error shown is the relative error to nominal *SAIL* CR parameters (plagiophile canopy, LAI = 4, $\theta s = 30°$) from the 12 study sites of *Acer saccharum* M. used in the present study, in relation to variable values of LAI, θs and canopy type.

For a given plagiophile canopy type (Figure 3 – middle) errors of less than 5% are found in the predicted bioindicator when LAI is higher than 3 and the optical indices used are the Red Edge Reflectance-Ratio Indices and Spectral and Derivative Red Edge Indices $(R_{740}/R_{720}$ optical index, Vogelmann *et al.*, 1993 is shown in the figure). These results indicate that bioindicator prediction in closed canopies with LAI > 3 are not affected by LAI variability. This further suggests that LAI variations between the 12 *Acer saccharum* M. study sites (2.85 to 5.17) in a plagiophile canopy have an insignificant effect on the optical indices and on the bioindicator prediction; less than 5% differences are expected relative to predictions made with a nominal LAI = 4.

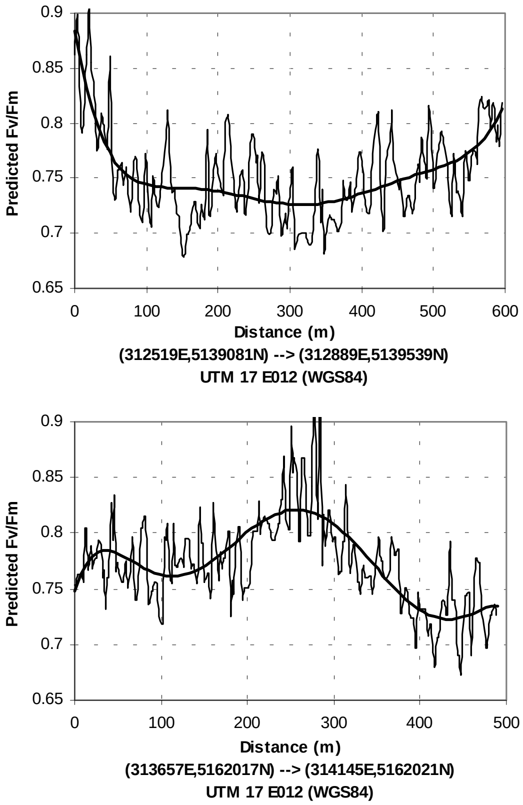

Figure 4. Transect estimation of Fv/Fm in the two study sites showing the lowest (upper plot) and highest (lower plot) values of Fv/Fm. Estimation made from Vogelmann (R_{740}/R_{720}) optical index calculated from *CASI* data scaling-up single-leaf reflectance measurements through *SAIL* CR model.

Results also demonstrate the small effect of θ_s especially in red edge spectral and derivative indices (Figure 3, middle and bottom). It shows the insignificant variation of the predicted bioindicator when θ_s changes from 20° to 60° where the optical indices used are Vogelmann (R_{740}/R_{720}) and DP21 ($D_{\lambda o}/D_{703}$), respectively. Therefore changes in θ_s from 29° to 41° in the 12 CASI images obtained from the study sites are not expected to affect the bioindicator prediction when $\theta_s = 30°$ was chosen as nominal input parameter in the CR model when scaling from leaf-level to canopy-level.

This study shows that derivative indices are less sensitive to low LAI values than other optical indices. Vogelmann (D_{715}/D_{705}), λ_p and DP21 ($D_{\lambda o}/D_{703}$) predict the bioindicator with only 15-20% error when LAI = 1 relative to the prediction with nominal LAI = 4. Non-derivative optical indices show higher errors: for example, Gitelson & Merzylak (R_{750}/R_{550}) 140%, Carter (R_{695}/R_{760}) 150%, Vogelmann (R_{740}/R_{720}) 65%, Gitelson & Merzylak (R_{750}/R_{700}) 200% for LAI = 1. This demonstrates that red edge and derivative indices are more suitable for bioindicator prediction and mapping with high spatial resolution hyperspectral remote sensing, where the effects of shadows and canopy openings can be selectively discriminated against in data analysis.

7 VALIDATION OF METHODOLOGY: A TRANSECT DATA COLLECTION

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.

Transect sampling collection across predicted site bioindicator variations has been designed for validation purposes. Two study sites with highest and lowest Fv/Fm have been selected for field data sampling along a 500 m transect. Ground-truth measurements of chlorophyll-*a*, chlorophyll *a&b*, carotenoids and Fv/Fm will be compared to estimations made from airborne *CASI* data through the methodology explained in this paper. Figure 4 shows the estimations of Fv/Fm in the mentioned study sites using the Vogelmann (R_{740}/R_{720}) optical index obtained from *CASI* data through *SAIL* CR model. Both transects from 1998 data show patterns with extreme Fv/Fm values that will allow comparison with the leaf samples.

Additional hyperspectral *CASI* data with 2.5 nm spectral resolution will be collected in the 1999 deployment in all *Acer saccharum* M. study sites. The 2.5 nm fibre spectrometer for leaf-level reflectance and transmittance measurements will allow the study of the spectral resolution influence in the calculation of optical indices. Additional sites of *Pinus strobus* L. and *Pinus banksiana* Lamb. have been included in the deployment in order to study the species dependency of the optical indices and algorithms developed.

8 CONCLUSIONS

This study demonstrates that leaf-level measurements of pigments and fluorescence along with leaf reflectance and transmittance can be used to produce algorithms to estimate these variables through above-canopy spectral reflectance models *SAIL* and *Kuusk*. Canopy structure was shown to play an important role in this link from leaf-level measurements to canopy-level hyperspectral data, affecting optical indices in different ways. A sensitivity study showed that low LAI values are very critical to the accuracy of predicted bioindicator regardless of the considered type of canopy. Differences between the predicted bioindicator using nominal canopy parameters and the prediction with variable θ_s and LADF is insignificant when LAI is higher than 3. Furthermore, the canopy type is irrelevant for the estimations when LAI is higher than 3 and the θ_s is a nominal 30°.

This study demonstrates that the algorithm development methodology presented here using nominal CR parameters from mapping bioindicators at this site is valid: LAI variability from the 12 *Acer saccharum* M. study sites in a plagiophile canopy and θ_s variability in the collected data have an insignificant effect in the optical indices and in the bioindicator prediction.

Finally, this study has shown that derivative indices are less sensitive to low LAI values than other optical indices. This demonstrates that red edge and derivative indices are more suitable for bioindicator prediction and mapping with high spatial hyperspectral remote sensing data.

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