Minimization of Shadow Effects in Forest Canopies for Chlorophyll Content Estimation Using Red Edge Optical Indices through Radiative Transfer: Implications for MERIS

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Abstract - This paper reports on progress made to develop methods to accurately estimate pigment content in forest canopies from airborne hyperspectral data. Radiative transfer approaches and red edge optical indices were applied to twelve sites of *Acer saccharum* M. in the Algoma Region, Ontario (Canada), where field measurements and hyperspectral CASI reflectance data have been collected between 1997 and 2000 deployments. Turbid-medium models such as SAILH and *Kuusk* were successfully applied to closed forest canopies minimizing the effects of canopy shadows and structure by using red edge optical indices in the merit function. Pigment content was successfully estimated linking PROSPECT leaf model to SAILH canopy model, minimizing the merit function by iterative process in MERIS-derived spectra from hyperspectral CASI data. The selection of the merit function used for minimization has been demonstrated to be critical, showing that shadow effects are removed when red edge optical indices are used. Implications for MERIS sensor by ESA on ENVISAT are discussed in this paper.

I. INTRODUCTION

The estimation of pigment content at a canopy level can be performed using simple statistical relationships at a leaf level through the use of optical indices, using modelling methods through radiative transfer by numerical model inversion [1]-[6], and by a combination of leaf-level empirical relationships coupled with a canopy reflectance (CR) model [7],[8]. Coupling leaf and canopy models for biochemical and biophysical parameter estimation by model inversion enables to consider the type of vegetation canopy and viewing geometry. CR models, such as SAILH [9] and MCRM [10],[11] used in this research, take into account viewing geometry and canopy structure, therefore modelling those effects in the canopy reflectance by different approximations generally based on the radiative transfer equation and geometrical optical considerations. Less complex assumptions of such turbid-medium models make its application to remote sensing easier since the number of input variables to be minimized decreases, although they lack the modelling of canopy structural variables that affect reflectance, such as canopy shadows and openings. The numerical model inversion of linked leaf and canopy models requires a merit function Δ^2 for a set of parameters $P=(N,Chl_{a+b},C_w,LAI,q_s\ldots)$ that minimizes the error between the modelled and sensor-measured canopy reflectance. The effect of selecting the merit function for biochemical and biophysical parameter estimation is demonstrated to be critical [12]. The effect of shadows and openings in the canopy reflectance for pigment content estimation using hyperspectral CASI data of 2 m spatial resolution and MERIS-simulated data is studied in this paper, and the implications for MERIS sensor discussed.

II. DATA COLLECTION

Airborne hyperspectral data acquisition was carried out with 0.5 m spatial resolution and 5 spectral bands, and with 2 m spatial resolution and 72 channels in the 400-950nm spectral range. Leaf samples were collected at each site for biochemical analysis and measurement of leaf chlorophyll *a+b* and carotenoid concentrations. Single leaf reflectance and transmittance measurements were acquired on leaf samples using a Li-Cor 1800 Sphere apparatus with a fibre spectrometer with 7.5 nm spectral resolution in the 400-900 nm range. Radiometrically calibrated CASI data were processed to *ground-reflectance* using the CAM5S atmospheric correction model with aerosol optical depth data collected in the study area at the time of data acquisition. Reflectance data were georeferenced using GPS data collected onboard the aircraft.

III. MERIT FUNCTION DEFINITION FOR THE RADIATIVE TRANSFER MODEL INVERSION

Numerical model inversion of a linked leaf and canopy model to estimate chlorophyll *a+b* requires minimizing a

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merit function by iterative optimization. The merit function $\Delta^2 = \sum_n [\rho_m(\lambda_i) - \rho^*(\lambda_i, P)]^2$ is used for error calculation when optimizing the set of parameters input for the leaf and canopy reflectance models. The measured canopy spectral reflectance $r_m(l_i)$ is compared to $r^*(l_i, P)$, the modelled canopy spectral reflectance calculated with a set of P parameters $P=(N, Chl_{a+b}, C_w, LAI, q_s \ldots)$. The critical role played by the merit function used for parameter estimation has been treated before [12],[13] showing that red edge spectral transforms such as R_{750}/R_{710} in the merit function minimize the effects due to forest canopy structure, shadows and openings in the measured canopy reflectance. Therefore this approach enables the use of less complicated radiative transfer models, such as turbid medium assumptions, for closed forest canopies.

IV. RESULTS AND IMPLICATIONS FOR MERIS

Results from 1997, 1998 and 1999 data over 12 study sites of *Acer saccharum* M. for chl_{a+b} estimation using the spectral transform R_{750}/R_{710} in the merit function showed that little effect is caused by shadows in the estimation of chl_{a+b} when the red edge optical index R_{750}/R_{710} is used in the merit function: RMSE=5.57 μg/cm^2 (targeting crowns, 2x2 m pixel size), RMSE=5.48 μg/cm^2 (all pixels including shadows, 20x20 m plot) with SAILH and PROSPECT inversion. A large effect is found when all reflectance channels are used in the minimizing function: RMSE=12 μg/cm^2 (targeting crowns), RMSE=23.1 μg/cm^2 (all pixels) [12],[13]. A validation of this methodology was carried out selecting a different set of 14 80x80m plots collected at 0.86x3.4m and re-sampled to 1.5x1.5m spatial resolution. This validation enabled us to propose an operational methodology for chl_{a+b} estimation in closed canopies using a satellite sensor with red edge spectral bands, such as MERIS by ESA, and to study its spectral capabilities for model inversion. MERIS equivalent spectra were calculated from the CASI-72-channel data in order to perform a simulation to study the applicability of MERIS red edge bands for pigment estimation by model inversion. Although careful atmospheric correction must be performed, two MERIS spectral bands located along the red edge, at 705 nm (10nm bandwidth) and 753.75 nm (7.5 nm bandwidth) are proposed for calculating the index R_{750}/R_{705} to be used in the merit function. The similar spectral bandwidth of the CASI sensor in the 72-channel mode of operation of 7.5 nm, allowed simulation of the MERIS centre wavelengths by interpolation from CASI hyperspectral data. MERIS-equivalent images were built from CASI data, and reflectance data extracted from the plots (Figure 1). The same methodologies were then carried out for chl_{a+b} estimation by model inversion using SAILH and $R_{\infty 3}$ infinite reflectance model [12] coupled with PROSPECT, using MERIS R_{750}/R_{705} red edge index. Results in Table 1 show that R_{750}/R_{705} used for MERIS performs similarly as R_{750}/R_{710} used for estimations with CASI, obtaining R^2=0.44, and RMSE=3.0 μg/cm^2 (SAILH + PROSPECT, targeting crowns), RMSE=3.97 μg/cm^2 (SAILH+PROSPECT, all pixels).

V. CONCLUSIONS

This work demonstrates that red edge optical indices used in the merit function for model inversion minimizes effects due to shadows and openings in forest canopies. This method enables the use of less complex radiative transfer turbid-medium models for pigment content estimation. Results show only a small effect when shadow pixels are included for the estimation of the chl_{a+b} using SAILH and PROSPECT inversion with the red edge optical index R_{750}/R_{710} in the merit function. On the other hand, a large effect due to inclusion of shadow pixels is found with SAILH and PROSPECT inversion when all reflectance channels are used in the minimizing function. MERIS-simulated data from hyperspectral CASI reflectance showed that MERIS index R_{750}/R_{705} achieved RMSE of 3 μg/cm^2 using PROSPECT+SAILH by model inversion. These results suggest that methodologies investigated here using red edge indices can be transferred to MERIS

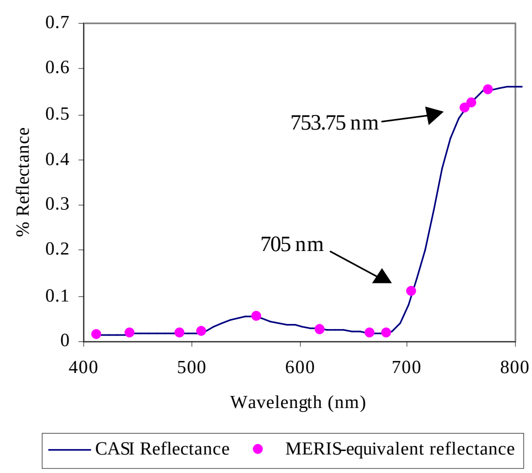

Figure 1. MERIS-equivalent spectra obtained from CASI 72-channel data showing the spectral bands proposed for model inversion through the red edge optical index R_{750}/R_{705}.

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Table 1. Comparison of RMSE and R^2 for chl_{a+b} estimation considering all pixels (including shadows) in the 80x80m area averaged reflectance of 0.86x3.4m re-sampled to 1.5x1.5m spatial resolution and 72-channel CASI data (2809 pixels), and selecting the upper 25% pixels in the NIR to minimize shadows and openings in a dense canopy of *Acer saccharum* M. (targeting crowns). MERIS-equivalent spectra were obtained from CASI 72-channel data, and R_{750}/R_{705} used for model inversion with SAILH and $R_{\infty 3}$ infinite reflectance coupled with PROSPECT.

	CASI 72-channel data					
	SAILH+ PROSPECT $D^2=f(SR_1)$		**SAILH+ PROSPECT** $D^2=f(R_{750}/R_{710})$		$R_{¥3}$ **+ PROSPECT** $D^2=f(R_{750}/R_{710})$	
	up	*all*	*up*	*all*	*up*	*all*
R^2	0.2	0.18	0.42	0.43	0.43	0.44
RMSE	4.8	14.8	3.0	5.2	5.0	8.9
	MERIS Simulation from CASI 72-channel data					
	SAILH+ PROSPECT $D^2=f(R_{750}/R_{705})$		$R_{¥3}$ **+ PROSPECT** $D^2=f(R_{750}/R_{705})$			
	Up	*all*	*up*	*all*		
R^2	0.44	0.44	0.43	0.43		
RMSE	3.0	3.97	3.9	6.98		

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