# Scaling-Up and Model Inversion Methods with Narrowband Optical Indices for Chlorophyll Content Estimation in Closed Forest Canopies with Hyperspectral Data

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***Abstract*—Radiative transfer theory and modeling assumptions were applied at laboratory and field scales in order to study the link between leaf reflectance and transmittance and canopy hyperspectral data for chlorophyll content estimation. This study was focused on 12 sites of *Acer saccharum* M. (sugar maple) in the Algoma Region, Canada, where field measurements, laboratory-simulation experiments, and hyperspectral compact airborne spectrographic imager (CASI) imagery of 72 channels in the visible and near-infrared region and up to 1-m spatial resolution data were acquired in the 1997, 1998, and 1999 campaigns. A different set of 14 sites of the same species were used in 2000 for validation of methodologies. Infinite reflectance and canopy reflectance models were used to link leaf to canopy levels through radiative transfer simulation. The closed and dense ($LAI > 4$) forest canopies of *Acer saccharum* M. used for this study, and the high spatial resolution reflectance data targeting crowns, allowed the use of optically thick simulation formulae and turbid-medium SAILH and MCRM canopy reflectance models for chlorophyll content estimation by *scaling-up* and by *numerical model inversion* approaches through coupling to the PROSPECT leaf radiative transfer model. Study of the merit function in the numerical inversion showed that red edge optical indices used in the minimizing function such as $R_{750}/R_{710}$ perform better than when all single spectral reflectance channels from hyperspectral airborne CASI data are used, and in addition, the effect of shadows and LAI variation are minimized. Estimates of leaf pigment by hyperspectral remote sensing of closed forest canopies were shown to be feasible with root mean square errors (RMSE's) ranging from 3 to 5.5 $\mu$g/cm$^2$. Pigment estimation by model inversion as described in this paper using these red edge indices can in principle be readily transferred to the MERIS sensor using the $R_{750}/R_{705}$ optical index.**

***Index Terms*—Chlorophyll, hyperspectral, leaf reflectance, optical indices, radiative transfer.**

Manuscript received September 2, 2000; revised February 6, 2001. This work was supported in part by the Centre for Research in Earth and Space Technology (CRESTech), the Ontario Ministry of Natural Resources, the Canadian Forestry Service, the Ministry of Environment and Energy, and Geomatics for Informed Decisions (GEOIDE), part of the Canadian Networks of Centres of Excellence Programme.

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Publisher Item Identifier S 0196-2892(01)05497-3.

## I. Introduction

EXTENSIVE research has been carried out at the leaf level in order to assess the physiological condition based on the study of the light interaction with the foliar medium. The total chlorophyll content in leaves decreases in stressed vegetation, changing the proportion of light-absorbing pigments and leading to less overall absorption with chlorophyll $a$ and $b$ ($\mathrm{chl}_{a+b}$) being the most important plant pigments absorbing blue and red light in the 430–660 nm region, respectively [1], [2]. Differences in reflectance between healthy and stressed vegetation due to changes in pigment levels have been detected in the *green peak* and along the *red edge* (690 to 750 nm) (e.g., [3]–[6]), allowing remote detection methods to identify vegetation stress and mapping through the influence of chlorophyll content variation [7]. Several narrowband leaf-level optical indices have been reported in the literature that might be applied to hyperspectral canopy reflectance data for $\mathrm{chl}_{a+b}$ estimation at larger scales [8], [9]. Nevertheless, most studies related to optical indices for vegetation functioning are based on measurements made at the leaf level rather than at the canopy level, where correlation between chlorophyll content and spectral reflectance can be readily observed [10]–[14]. These potentially valuable optical indices, both traditional and new developed narrowband indices derived from recent research based on reflectance and derivative spectra, are grouped into four categories, based on the spectral region and the type of parameter used [8], [9], [15]–[17].

1) *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 $(R_{440}/R_{690})$;
2) *Visible/NIR Ratios*: NDVI $(R_{774} - R_{677})/(R_{774} + R_{677})$; SR $(R_{774}/R_{677})$; Lichtenthaler $(R_{800} - R_{680})/(R_{800} + R_{680})$, $(R_{440}/R_{740})$; and SIPI $(R_{800} - R_{450})/(R_{800} + R_{650})$;