

Algorithm of Retrieving Needle Leaf Chlorophyll Content from Hyperspectral Remote Sensing

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Abstract- In this paper, we report on a process-based approach to estimate leaf chlorophyll content from hyperspectral remote sensing imagery. Extensive field and laboratory measurements were conducted for ten sites in black spruce (*Picea mariana*) forests near Sudbury, Ontario, Canada in 2003 and 2004. Leaf optical spectra and chlorophyll content, leaf and canopy biophysical parameters, and forest background optical properties were collected. Hyperspectral remote sensing images were acquired by the Compact Airborne Spectrographic Imager (CASI) over the study sites within one week of ground measurements. Using measured data as inputs, a geometrical-optical model 4-Scale was investigated to estimate forest canopy reflectance. The simulated canopy reflectance agrees well with the CASI measured reflectance. A look-up-table approach was developed to provide the probabilities of viewing sunlit foliage and background, and to determine a spectral multiple scattering factor as functions of leaf area index, view zenith angle, and solar zenith angle. With the look-up-tables, leaf reflectance spectra were inverted from hyperspectral remote sensing imagery. Leaf chlorophyll content was estimated from the retrieved leaf reflectance spectra using the modified leaf-level PROSPECT inversion model.

Key Words: Needle leaf, Chlorophyll content, Retrieval, Hyperspectral remote sensing

I. INTRODUCTION

Spectrally continuous hyperspectral remote sensing data are useful for estimating forest biophysical and biochemical parameters. Leaf

chlorophyll content is the main parameter determining leaf spectral variation in the visible regions. Quantitative estimates of leaf chlorophyll content from hyperspectral remote sensing can provide a useful means for assessing forest condition and stress levels as affected by insects and diseases. Estimation of canopy-level biochemical contents is usually performed by using leaf-level relationships between optical indices and pigment content[1]-[2], or statistical relationships between ground-measured biochemical contents and canopy reflectance measured in the field or by airborne or satellite sensors[3]-[4], or by inverting coupled leaf and canopy RT models or ray-tracing models[5]-[6]. At the canopy scale, especially for heterogeneous, open, and clumped forest canopies, canopy structural effects on remote sensing signals are considerable. To retrieve leaf-level information from remote sensing measurements above open forests with distinct structural effects, new methodologies need to be developed. This paper reports on a process-based approach to estimate leaf-level reflectance from canopy-level hyperspectral remote sensing measurements by removing canopy structural effects, and thereby to infer leaf chlorophyll content.

II. STUDY SITES AND DATA COLLECTION

Study sites include ten black spruce (*Picea mariana*, abbreviation SB) stands selected near Sudbury, Ontario, Canada (46° 49' 13" to 47° 12' 9" N, 81° 22' 2" to 81° 54' 30" W). The ten sites are of different ages, growth conditions, and crown closures. Near each site, at least two 2×2 m white ground targets were arranged as the ground control points for the remote sensing

image registration. Two 50 or 60-meter-long parallel transects separated by 20 m were set up at each site in the east-west or southeast-northwest direction. In 2003 and 2004, forest structural parameters (LAI, effective LAI, and clumping index) were measured on the two transects using complementary optical instruments including TRAC (Tracing Radiation and Architecture of Canopies), LAI-2000 (Plant Canopy Analyzer, LI-COR, Lincoln, NE), and digital hemispherical photography techniques (Nikon CoolPix 4500 and a Nikon FC-E8 fisheye lens) with a photographic exposure protocol [7]. Shoots were sampled with a shotgun from the top of tree crowns of five medium trees at each site by the crew of the Ontario Forest Research Institute (OFRI). The average needle adaxial reflectance and transmittance were measured at a 1 nm spectral interval using a portable field spectroradiometer FieldSpec Pro FR (Analytical Spectral Devices, Inc. Boulder, USA) attached via a fiber optic cable to a Li-Cor 1800 integrating sphere (Li-Cor 1800-12S, Li-COR, Inc., Lincoln, Nebraska, USA). Needle thickness and width were measured with a digital caliper (Marathon Company, Canada); subsequently, OFRI analyzed needle chlorophyll_{a+b} content in the laboratory. In addition, shoots were sampled for measuring needle-to-shoot area ratio. A digital camera (Toshiba PDR-4300) mounted on a firm copy stand (Regent Instruments Inc., Canada) was used to measure shoot area projected on a light table (Kaiser Prolite 5000, Germany) at three camera incident angles: 0°, 45°, and 90° relative to the shoot main axis at 0° azimuth angle. Shoot projected area was analyzed using the image analysis software WinSEEDLE (Regent Instruments Inc., Canada) to derive needle-to-shoot area ratio. At each site, forest floor cover types, and the corresponding reflectance of each cover type were measured to determine the average forest background reflectance. Compact Airborne Spectrographic Imager (CASI) imagery were acquired using a *hyperspectral* mode, with a 2 m spatial resolution and 72 channels at a 7.5 nm spectral

resolution covering the visible and near infrared range from 408 nm to 947 nm, over the ten black spruce sites on September 5, 2003. The CASI imagery was atmospherically corrected and geometrically referenced using the GPS data collected at the center of 2×2 m ground white targets. Mean reflectance of 20×20 m from the image was calculated for each site for analysis and modeling purposes.

III. METHODOLOGY

To estimate leaf chlorophyll content from canopy-level hyperspectral remote sensing imagery, the following procedures were conducted (Figure 1):

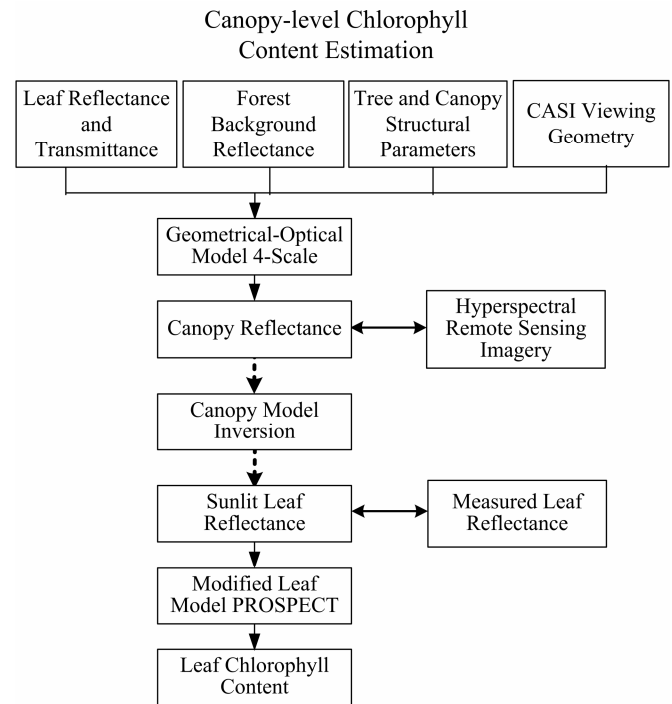


Figure 1: Methodologies for retrieving needle leaf chlorophyll content from canopy-level hyperspectral remote sensing measurements

A. Estimation of canopy reflectance and forest scene components

The geometrical-optical models 4-Scale [8] describes forest canopy architecture using simple geometry, and has the capability of simulating the canopy reflectance of both open and closed canopies. The model was investigated to estimate the canopy reflectance and the probabilities of viewing forest scene components:

sunlit tree crown, shaded tree crown, sunlit background, and shaded background:

$$R = R_T P_T + R_{ZT} P_{ZT} + R_G P_G + R_{ZG} P_{ZG} \quad (1)$$

where R is the canopy reflectance; R_T , R_{ZT} , R_G , and R_{ZG} are the reflectivities of the sunlit tree crown, shaded tree crown, sunlit background, and shaded background respectively; P_T , P_{ZT} , P_G and P_{ZG} are the probabilities of a sensor viewing the sunlit and shaded tree crowns, sunlit and shaded background, respectively. The 4-Scale model can be run with a set of tree architectural parameters, forest biophysical parameters, and leaf and forest background optical properties, though many input parameters are required.

B. Canopy model inversion for retrieving leaf reflectance

To fulfill the model inversion, a multiple scattering factor was introduced to include the contributions of the two shaded components, and to convert the reflectivity of the sunlit foliage (R_T) to the reflectivity of an individual leaf R_L . Given that canopy reflectance R can be remotely measured and forest background reflectivity R_G is known from ground measurements, a look-up-table (LUT) method was developed to invert the model. One site with medium foliage coverage and clumping index was selected to generate LUTs by the 4-Scale model. Two LUTs were produced to take into account different canopy structural configurations and viewing geometry. for this purpose. One LUT provides the probabilities of viewing the sunlit foliage P_T and background P_G components, and the other LUT provides the spectral multiple scattering factors MS to convert the average reflectivity of sunlit leaves to the reflectivity of an individual sunlit leaf. With the LUTs, measured forest background reflectance, and the canopy reflectance from remote sensing images ($R \approx R_{CASI}$), the sunlit leaf reflectivity R_L can be derived:

$$R_L = \frac{R_{CASI} - R_G \times P_G}{P_T \times MS} \quad (2)$$

where R_{CASI} is the mean reflectance of the site from CASI imagery.

C. Leaf-level chlorophyll content retrieval

Using the leaf reflectance estimated from (2), and the leaf transmittance spectra derived based on the spectral ratio of laboratory measured leaf reflectance to transmittance as inputs, leaf chlorophyll content was estimated using the modified PROSPECT model, which is suitable for needle leaf species by incorporating needle thickness and width parameters in PROSPECT to take into account the edge effects of needles on light transfer through them and the geometrical effects of the needle-holding device on needle leaf spectra measurements [9].

IV. RESULTS AND DISCUSSION

With the measured leaf optical properties (reflectance and transmittance spectra), forest background reflectance, a set of tree architectural parameters for black spruce species, canopy structural parameters (LAI, clumping index, needle-to-shoot area ratio), and CASI acquisition geometry (solar zenith angle, view zenith angle, and azimuthal angle), 4-Scale was run to estimate the canopy reflectance and the probabilities of viewing four forest scene components. The estimated canopy reflectance of black spruce sites agrees well with the CASI measurements from the visible to the near-infrared ranges, with slight discrepancies in the blue and near-infrared region. The discrepancies between modeled and measured reflectance by CASI range from 0.24% to 3.28% in the blue region, 0.01% to 1.60% in the green and red regions, and 0.01% to 4.44% in the near-infrared region.

The retrieved sunlit leaf reflectance is in reasonable agreement with the laboratory measured leaf reflectance ($R^2=0.89$ to $R^2=0.97$). In the red region of 600-700 nm, where a leaf has strong absorption, the model generates good estimates. The discrepancy between the inverted and measured leaf reflectance is in a range of 0.04% to 4.45%. The retrieval of leaf reflectance is sensitive to the canopy reflectance. In the near-infrared region, small variation in CASI reflectance causes large discrepancies between the measured and inverted leaf reflectance. The

discrepancy between these two spectra is in a range of 0.01% to 11.80% from 700 to 908 nm.

Figure 2 shows the results of needle chlorophyll content retrieval for the black spruce sites. Compared to the measured average needle chlorophyll_{a+b} content of the nine sites (with a range of 24.9 $\mu\text{g}/\text{cm}^2$ to 37.6 $\mu\text{g}/\text{cm}^2$), needle chlorophyll_{a+b} estimation yields an accuracy of $R^2=0.47$ and $\text{RMSE}=4.34 \mu\text{g}/\text{cm}^2$.

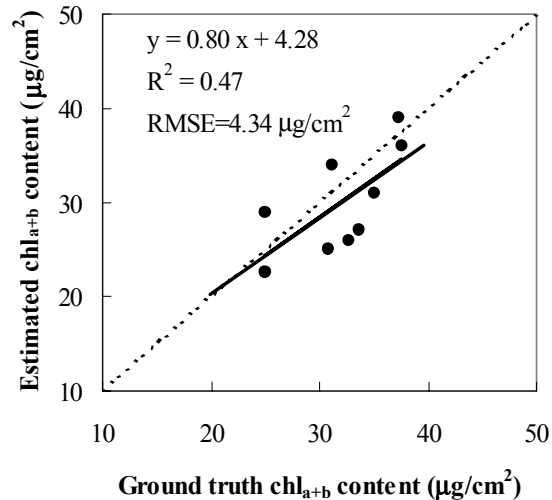


Figure 2. Comparison for needle chlorophyll content from the measurements and from the process-based model inversion.

V. CONCLUSION

The confounding effects of canopy structure make chlorophyll retrieval from canopy-level remote sensing complicated and challenging. This research developed a process-based method to estimate needle leaf chlorophyll content from hyperspectral remote sensing imagery for complex forest canopies. The structural effects of forest canopies and forest background are successfully removed to fulfill the retrieval of leaf-level spectra information from above-canopy remote sensing measurements. The demonstration of this process-based approach points to a future direction of retrieving vegetation information from hyperspectral remote sensing imagery.

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