Chlorophyll Content Estimation of Boreal Conifers using Hyperspectral Remote Sensing

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Abstract*—This investigation quantitatively links physiologically based estimators of forest stand condition, such as chlorophyll concentration, to hyperspectral observations of Jack Pine (Pinus Banksiana), a dominant Boreal Forest species. Between June and September of 2001, four Intensive Field Campaigns (IFC) of data collection were conducted over the forested areas near Sudbury, Ontario, Canada. Using the CASI sensor, data were collected, in the visible and near infrared domain, over eight selected Jack Pine sites. Supplementing the airborne campaigns, was simultaneous on-site collection of foliage samples for laboratory spectral and chemical measurements. The study first linked needle-level reflectance and pigment content through the inversions of leaf level radiative transfer models such as PROSPECT. Next, the red-edge index (R750/710), was scaled up to the canopy level through the use of canopy models and infinite reflectance calculations, which simulate the canopy as an optically thick vegetation medium. However, for the relatively open and clumped jack pine stands such a simple approach requires careful validation due to the confounding effects of the open canopy structure. Accordingly, the analysis has focused on high spatial resolution CASI imagery (1 meter) for which tree crowns, shadows, and open (sun-lit) understory can be identified visually and approaches can be examined for validity and effects. Effectively eliminating these confounding variables will permit the generation of predictive needle pigment content maps for forest condition assessment.

Keywords- Chlorophyll, Pinus Banksiana, needle reflectance, forest monitoring

I. INTRODUCTION

Airborne hyperspectral remote sensing platforms, such as the Compact Airborne Spectrographic Imager (CASI), offer the potential to retrieve biochemical parameters of boreal canopies, thereby permitting a greater understanding of vegetation productivity and forest stand condition. Although connections between leaf biochemistry and optical properties have been empirically established for decades, additional research is required to determine if modeling techniques for coniferous canopies are feasible. Inherent difficulties in measuring optical properties of conifer needles, due to their structure and relative thickness, have inhibited previous modeling approaches to provide quantitative predictions of needle chlorophyll content from conifer spectral data. Using recent methodologies to systematically measure spectral properties of conifer needles [1], this investigation focused on linking Jack Pine (*Pinus Banksiana*) optical characteristics to forest stress indicators, such as chlorophyll concentration.

II. EXPERIMENTAL MATERIALS

A. Study Area

The study area for this experiment comprised of eight Jack Pine sites near Sudbury, Ontario, Canada. The forest plots were selected by the Ontario Forest Research Institute (OFRI) and were added to the *Bioindicators of Forest Condition Project*, an initiative to develop a Forest Condition Rating (FCR) system to quantitatively classify stand health using remote sensing techniques [2]. The Jack Pine sites were selected based on their relative health condition, age, crown closure, and ease of access from road networks. It is necessary to consider both stressed and healthy forest plots, thereby providing a range of physiological conditions, to test algorithms for monitoring forest physiological conditions. Furthermore, the relatively open and clumped nature of Jack Pine stands introduces additional challenges in site selection and parameter retrieval. Within each site, 5 representative trees within a 20 x 20 meter area were marked and used for needle sample collection in all field campaigns.

B. Needle-level data

Needle samples were collected from the Jack Pine plots during four Intensive Field Campaigns (IFC), between June and September of 2001. Foliage from the upper canopy (exposed to sunlight) was acquired from the five representative trees within each site. The samples were harvested using a shotgun and were temporarily stored in coolers during transport to the field laboratory, where reflectance and transmittance measurements were acquired. In the selection of the needles for spectral and chemical analyses, first year needles were measured separately from older foliage from the same shoot.

Needle reflectance and transmittance measurements were acquired using an Analytical Spectral Devices Full Range Spectroradiometer coupled with a Li-Cor 1800 integrating sphere. The protocol for spectral measurements employed a black anodized carrier to present only the needle surfaces to the integrating sphere [1]. After the necessary spectral measurements were recorded, the samples were stored in a freezer and transported to the Ontario Forest Research Institute laboratory for chlorophyll content extraction.

C. Canopy-level data

Complementing the needle collection campaigns were airborne missions of image acquisition. Compact Airborne Spectrographic Imager (CASI) imagery, in the visible and near infrared region, was collected over the study plots. Imagery for this experiment was acquired in two different modes: a) multispectral mode with spectral data at 7 bands and a spatial resolution of 1 meter, and b) hyperspectral mission mode with 72 spectral channels and 2 meter spatial resolution. After sensor radiometric calibration, all imagery were atmospherically corrected using the CAM5S model [3] to convert at-sensor radiance to at-surface modeled reflectance. Finally, images were geometrically corrected using Global Position System (GPS) coordinates from on-site targets.

III. EXPERIMENTAL METHODS

The investigation first linked needle reflectance properties with chlorophyll concentration through the inversions of PROSPECT [4], a leaf-level radiative transfer model (Figure 1). An iterative approach was employed to minimize a standard root mean square error– (RMSE) to retrieve chlorophyll a+b concentration from measured needle reflectance and transmittance spectra. The model-based estimates were scaled using an empirically determined geometric form factor (F), which adapts the needle shape to fit the constraints of a plate model, such as PROSPECT. Using photomicrographs of needle cross sections, the form factor was measured for 85 Jack Pine needles.

Spectral indices from reflectance signatures offer the potential approach to correlating optical properties with biochemical constituents. For closed canopy deciduous stands with Leaf Area Index (LAI) greater then 3, there is virtually no effect of shadows with an approach in which chlorophyll sensitive indices were simulated with models and compared to observed above canopy reflectance [5]. Scaling-up such indices for comparatively open and clumped Jack Pine stands requires careful validation. Accordingly, this investigation focused on high spatial resolution CASI imagery (1 meter) from which tree crowns, shadows, and open (sun-lit) understory were visually identified. The R750/R710 red-edge index was scaled-up to the canopy level using two methods. Firstly, the PROSPECT leaf model was coupled with an infinite reflectance model [6] to simulate an optically thick canopy. A second approach linked PROSPECT with the SAILH model [7]. In this turbid medium model, the canopy architecture is characterized by parameters such as LAI, Leaf Angle Distribution Function (LADF), and viewing and illumination geometries. The following nominal values were used in the simulations: hotspot size = 0.008, LAI = 6.0, LADF = spherical, solar zenith angle = 30^0, and viewing angle = 0^0. All canopy parameters were held constant and the R750/R710 index was scaled up as a function of varying chlorophyll content.

CASI multispectral mode imagery (1 x 1meter pixels) was used to isolate conifer crowns and calculate the R750/R710 index. Spectral profiles were extracted from the plot locations to identify reflectance properties of shadowed areas. Spatial masks were generated using thresholding techniques to effectively eliminate these shadowed areas from the analysis. Omitting shadow pixels allows for a more accurate retrieval of the red-edge index, which in turn results in a more representative estimate of conifer crown canopy content for forest condition assessment and mapping.

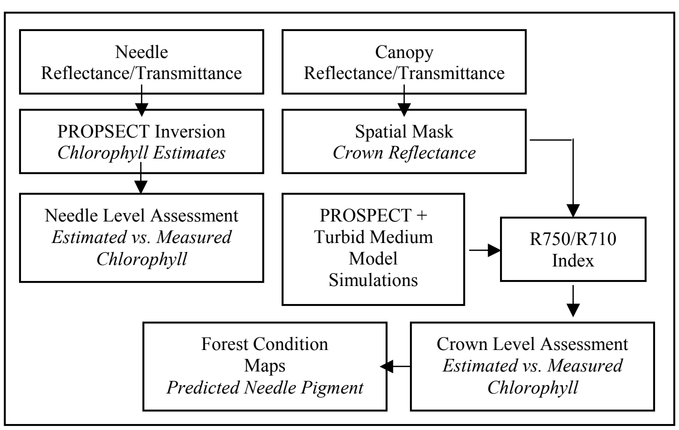

Figure 1. Methodology for needle and crown-level assessments of chlorophyll content

IV. EXPERIMENTAL RESULTS AND DISCUSSION

A. Needle-level

PROSPECT estimated needle level pigment content were compared with laboratory measurements (Figure 2). The estimated chlorophyll concentrations were scaled by a geometric form factor, which was measured to be 0.76. In addition, optimal geometric form factors were determined by minimizing the least squares difference between PROSPECT retrievals and laboratory measurements. The optimal form factors were 0.50 and 0.70 for old and new needles, respectively. The needle level assessment reveals that the PRO-

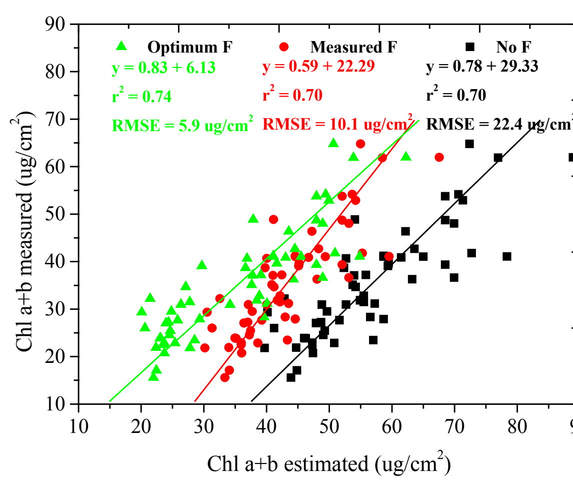

Figure 2. Inclusion of measured form factor (F) improves chlorophyll retrieval RMSEs from 22 ug/cm^2 to 10 ug/cm^2.

SPECT model with the form factor modification yielded RMSE of approximately 10 ug/cm^2, with a chlorophyll range of 15 ug/cm^2 to 65 ug/cm^2. It is important to note that the inclusion of the form factor does not affect the determination coefficient (r^2), but rather scales the chlorophyll estimates to allow for better comparison with measured pigment values.

B. Canopy-level

After the exclusion of shadowed areas, mean plot values of the R750/R710 index were calculated and compared with the coupled PROPSECT and turbid medium model simulations to derive crown chlorophyll estimates. The crown-level assessment of estimates with laboratory measured pigment content generated an RMSE of 6.54 ug/cm^2 using the infinite reflectance model and an RMSE of 4.48 ug/cm^2 with the SAILH model (Figure 3). These results reveal improvements from previous inversion methods for pigment retrieval from coniferous canopies [8]. The improvements can be attributed to several reasons. Firstly, the inclusion of a measurable geometric form factor improves chlorophyll retrievals, as witnessed at the needle-level. Furthermore, the relative difference in the chlorophyll content between new and old needles and its implications on canopy level estimates were addressed. Needle counts along representative branch shoots were conducted to determine that a typical Jack Pine plot within the study area exhibited an old/new needle proportion of approximately 75%. As a result, chlorophyll retrievals incorporated this age proportionality weighting factors into the crown-level assessment.

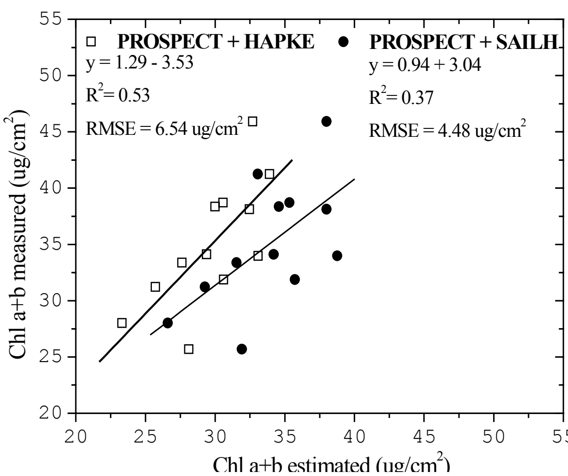

Figure 3. Crown-level pigment retrievals using PROSPECT coupled with Hapke infinite reflectance (r^2= 0.53) and SAILH model (r^2= 0.37). Retrievals were weighted with measured age proportionality of 75% old needles

C. Forest Condition Mapping

Using the crown level retrievals of chlorophyll content and the spatial masks that accounted for shadowed areas, needle pigment content maps were created using the multispectral CASI imagery (Figure 4). This simple approach provides a potential operational approach of mapping bioindicators using airborne remote sensing technology. Nevertheless, there are several issues, such as the influence of understory vegetation

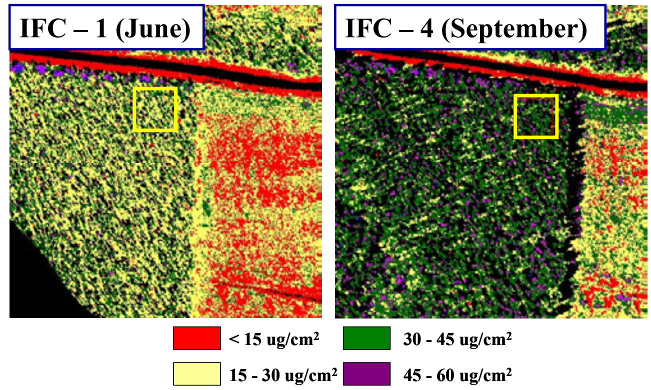

Figure 4. Change in estimated stand pigment content for one Jack Pine plot from June to September, 2001.

and its seasonal dynamics that must be considered. The reflectance signal from the understory confounds the above canopy observations, especially for typical open and clumped Jack Pine stands. Additional research is currently being conducted to account for the understory influence in crown level chlorophyll estimations of Boreal conifers.

V. Conclusions

This investigation has successfully adapted the PROSPECT model using the geometric form factor to link Jack Pine needle optical properties to forest stress indicators, leaf chlorophyll content in this case. In scaling-up needle level findings to the canopy level careful attention was given to needle sampling strategy (sunlit branches) and old versus new needle proportionality in Jack Pine stands. The coupled use of PROSPECT and canopy level turbid medium models, estimated crown-level chlorophyll concentration, provided that the confounding factor of shadows can be eliminated.

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