Combining hyperspectral remote sensing and physical modeling for applications in land ecosystems

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Abstract—— **Land ecosystems, in particular forest ecosystems, are under increasing pressure from environmental changes such as population growth, global warming, wildfires, forest insects, and diseases. Data from hyperspectral sensors can be used to map forest species and determine biophysical and biochemical properties. Modeling plays an important role in accurate determination of ecosystem properties. Radiative transfer models are used to understand how radiation interacts with the atmosphere and the Earth's terrestrial surface and to correct observed radiances to surface reflectance. Canopy models are used to infer through inversion quantitative information from hyperspectral data on canopy structure and foliage biochemistry. This article presents an overview on combining hyperspectral sensing with canopy radiative transfer models to derive ecosystem information products.**

Keywords: hyperspectral, ecosystem, radiative transfer model, vegetation indices, AVIRIS, EO-1, CHRIS, forestry, bioindicator.

I. INTRODUCTION

Earth observation from space relies on radiation measured by sensors. The signal depends on the way radiation interacts with the atmosphere and the Earth's terrestrial surface. The complexity of the interaction has promoted the development and use of empirical methods (e.g. vegetation indices). Most of these are based on quantitative, statistical relationships applied to a few images, which limits their robustness and use over large areas [1]. Radiative transfer models, using complex mathematical methods, simulate and provide insight into the radiation interaction processes for varying vegetative parameters. Remote sensing imaging spectrometers have evolved with respect to larger spectral resolution imaging spectrometers (e.g. NASA's AVIRIS, NASA's Hyperion on EO-1, Itres' casi, HYMAP, AISA), increased signal-to-noise ratios, 12-bit (and higher) quantization, and multi-directional sampling capabilities (e.g. ESA's CHRIS PROBA). These improvements have stimulated the development of better models and opened up new prospects for retrieval of more detailed environmental information from these advanced sensors [2].

Physical-based, quantitative canopy models compute vegetation canopy reflectance given leaf and canopy parameters (chlorophyll content, water content, leaf area index, etc.), a selected sun-target-sensor geometry, and information about the background (e.g. soil). Canopy models can be used in direct (forward) mode to build new vegetation indices optimized for a particular sensor [3]. Moreover, such models can be inverted against measured reflectance data to derive surface biophysical and structural parameters such as leaf area index (LAI), fraction of photosynthetically active radiation (fPAR), and vegetation fractional cover, which are used by ecologists to monitor the status and quantify the influence of vegetation.

In contrast to multi-spectral sensors, hyperspectral sensors can produce quantitative estimates of canopy biochemical properties (such as chlorophyll and nitrogen concentrations) [4]. Classification of hyperspectral imagery yields not only higher accuracy in land-cover characterization, but also of species recognition when compared to traditional remote sensing data sources such as Landsat [5]. Forest biomass and carbon have been estimated employing both multi-sensor techniques [6] and AVIRIS data using partial least squares (PLS) regression [7]. Estimates of the chemical concentrations (chlorophyll, nitrogen, lignin, water content) of forest canopies can be made using hyperspectral data [8].

Canopy models were used to simulate hyperspectral top-of-canopy reflectance values for analysis of various biophysical and biochemical factors affecting canopy reflectance [9]. Recently, canopy models have been employed to infer quantitative information from hyperspectral data on canopy structure and foliage biochemistry, such as LAI [10, 11], leaf/needle chlorophyll content [12], and foliage water content [13-15]. Hyperspectral imagery and canopy models were also used to analyze biological invasion, biogeochemical change [16] and nutrient availability in tropical ecosystems [17]. Very high spectral and spatial resolution imaging spectrometer data were used in Malenovsky et al. [18] to separately assess sunlit and shaded crowns of a Norway spruce canopy and quantify the impact of woody elements (e.g. trunks, first order branches and small woody twigs) in turbid media modeled cells using the 3-D radiative transfer model DART [19] to further refine the retrieval of forest relevant ecosystem parameters.

These land ecosystem information products can be used in forest disaster detection, invasive species mapping, Kyoto Protocol information products, monitoring forest health, ecosystem protection, and global change.

II. MODELS

The existing canopy reflectance models can be categorized into geometric models, turbid-medium models, hybrid models and ray tracing models. Geometric models [20-22] use geometric optics and radiative transfer theory to compute the reflectance from a plant canopy as a function of various structural (e.g. tree shape, tree height) and spatial parameters (e.g. stand density). Different scenes are modeled as varying proportions of shadowed and illuminated tree crowns, and shadowed and illuminated background. Such models are appropriate for and have been successfully used in sparse canopy situations.

In contrast, turbid medium models consider the plant canopy as a collection of absorbing and scattering particles, e.g., leaves and trunks, with given spectral properties which are distributed randomly in horizontal layers with specific orientations [23]. Turbid-medium models are more appropriate for applications in denser and horizontally uniform canopies [24]. Hybrid models [25, 26] apply the principles of both geometric and turbid medium models. In such models, vegetation canopy is simulated as a distribution of geometric objects which are composed of absorbing and scattering particles. The hybrid models can be applied to both sparse and dense canopies.

The ray tracing model [27-29] is another class of physical-based models. A three dimensional canopy is simulated on a computer with consideration of the arrangement and orientation of the vegetation. The Monte Carlo approach is commonly applied to study the scattering of light beams by plants. Although requiring intensive computing resources, these models allow a more realistic representation of the vegetation canopy [29].

III. LAND ECOSYSTEM INFORMATION PRODUCTS

Hyperspectral remote sensing combined with canopy radiative transfer models can provide consistent and accurate information products. This section summarizes the products derived from hyperspectral remote sensing data that can be used for the applications in land ecosystems. A few case studies at the Greater Victoria Watershed District (GVWD) were used to demonstrate the capabilities of hyperspectral remote sensing in deriving land ecosystem information products.

At the GVWD study site, Goodenough and colleagues [5-8, 30-32] have conducted extensive studies on forest species classification, biochemical mapping, and biomass estimation using hyperspectral data. The GVWD study site is located on Vancouver Island, British Columbia, Canada. The Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data were acquired both in 2001 (20 m spatial resolution) and 2002 (4 m spatial resolution). EO-1 Hyperion data were collected in 2001. The 20 m AVIRIS data were used in conjunction with 30 m EO-1 Hyperion data. Ground spectra, at 2.5 nm spectral resolution, were collected using an Analytical Spectral Devices (ASD) spectroradiometer at the time of image acquisitions. Calibration targets consisted of a grassy field (bright target) and a deep-water lake (dark target). The ground spectra collected from the ASD were associated to corresponding AVIRIS and Hyperion data using Global Positioning Satellite (GPS) data. Measurements of foliar chemistry were also collected over two years at this site.

A. Classification of land ecosystems

The accurate mapping of land cover into distinct classes is crucial for applications in land ecosystems. The classification accuracy of multi-spectral remote sensing is limited by the spectral resolving ability. With more variables (bands) than multi-spectral remote sensing data, hyperspectral data can theoretically give more accurate results in classification. The studies at GVWD [5, 30] have shown that hyperspectral remote sensing increased the accuracy of forest species classification from 77% with Landsat to over 90% with Hyperion and AVIRIS data (Table I).

TABLE I. CLASSIFICATION ACCURACY USING AVIRIS AND HYPERION. MODIFIED FROM [30].

	AVIRIS	**Hyp 1b (2-12)**
Class Label	**Accuracy %**	**Accuracy %**
Exposed Land	100	100
Water Body	99.4	99.8
Shrub Low	99.4	100
Herb Graminoids	100	100
Wet Land	94.5	97.1
Red alder Dominant	89.4	91.5
Hemlock Dominant	88.8	83.0
Lodgepole pine Dominant	89.4	87.7
Western redcedar Dominant	88.2	83.3
Douglas fir Dominant	90.5	92.5
Overall accuracy with 70% of the training data	94.0	94.2
Accuracy with 30% of the test data	92.1	90.0

B. Estimation of forest biophysical properties

With more accurate classifications of land cover, it is possible to map other forest biophysical properties to higher accuracy. At the GVWD study site, forest biomass was estimated using the 2002 AVIRIS data [7]. The Variable Density Yield Prediction (VDYP) model, developed by the Research Branch of BC Ministry of Forests, was used to calculate biomass reference data for 33 pseudo plots (60m by 60m). The VDYP was designed to predict average yields over large areas. It is intended for use in unmanaged stands of pure or mixed species composition. The PLS regression was employed to establish the relationship between the plot biomass truth and plot spectra. The average reflectance around plot centers gave a biomass prediction with an R^2 of 0.82 (Figure 1).

By combining canopy reflectance models and hyperspectral data, we can retrieve other forest canopy parameters, including canopy closure, LAI, or stand density. Asner et al. [33] have shown that through end member extraction and modeling methods, it is possible to map forest regrowth, new logging, primary forest, and underlying surface litter and slash in the Amazon forests. In a study site near Candle Lake, Saskatchewan, Canada, Chen et al. [11] used a canopy radiative transfer model, named 4-Scale [26], to perform BRDF corrections on *casi* images and improve the estimation of LAI and crown closure (CC). Schaepman et al. [34] demonstrated that the biophysical and biochemical variables of conifer forests (LAI, fractional cover, water content, and dry matter) can be retrieved successfully with reasonable root mean square errors from imaging spectrometer data by model inversion.

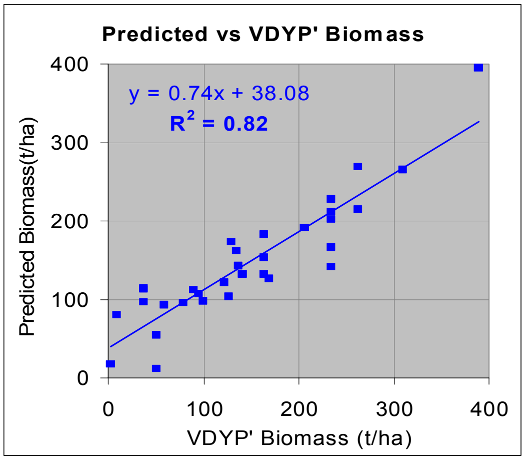

Figure 1. Forest biomass predicted by AVIRIS data and PLS vs. biomass simulated by VDYP. Modified from [7].

C. *Estimation of forest biochemical properties*

Hyperspectral data contain information of chemical composition in their absorption features. This makes it possible to estimate foliar chemical concentrations, such as chlorophyll-a and –b, nitrogen, lignin, and water content. For example, at the GVWD study site, foliar nitrogen concentration has been mapped successfully with hyperspectral data by Goodenough et al. [32], where the coefficients of determination were over 0.8 between measured and predicted nitrogen concentrations (map in Figure 2) and 0.79 for chlorophyll content. In these studies the hyperspectral data were converted to absorbance and transformed to derivatives for use in the PLS regression.

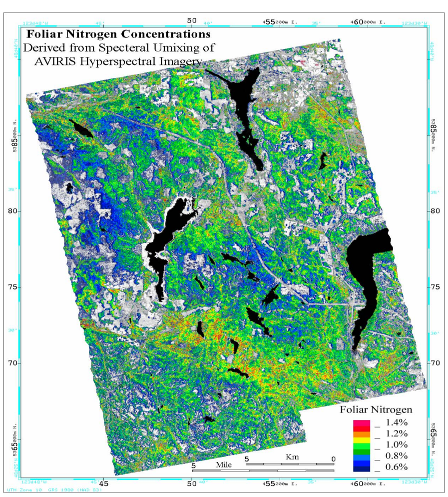

Figure 2. Nitrogen concentration map for GVWD derived by PLS using the 2nd derivative absorbance. Modified from [32].

In addition, a physical approach using a canopy radiative transfer model was also used to estimate fuel moisture content (FMC, % of needle dry mass) from hyperspectral data. The more accurate classification results from the AVIRIS images were used to select Douglas-fir dominant pixels. The Forest Reflectance and Transmittance (FRT) model [25] was used to simulate canopy reflectance and generate lookup tables. Fuel moisture content of Douglas-fir can then be determined from the AVIRIS image by the lookup table method. The estimates of FMC were compared with the field measurements. A R^2 value of 0.74 was achieved for tall Douglas-fir trees with closed canopy [35].

IV. PRODUCT APPLICATIONS

The applications of land ecosystem information products have been demonstrated in a wide range of environmental studies. This section highlights the applications to which the hyperspectral remote sensing has the greatest contribution.

A. *Forest disaster detection*

Forest disaster detection, such as forest disease (Dutch elm disease, root rots, mistletoes), insect infestation (bark beetles, defoliators, weevils), and fire, is important to forest managers who want to minimize environmental impact and timber losses. Lawrence and Labus [36] demonstrated that hyperspectral remote sensing with high spatial resolution could successfully detect tree stress resulting from Douglas-fir beetle attack. By taking advantage of spectral resolution afforded by hyperspectral data, it was possible to identify different levels of tree stress that could not be detected by multi-spectral imagery. The information on the early stages of insect attack can be used to fight early infestations ('green attack'), and thus reduce economic loss and adverse environmental effects.

The fire properties (fire temperature) and background information (fuel type and fuel moisture) derived from hyperspectral imagery can provide inputs for better fire spread modeling. For example, Dennison and colleagues [37] used AVIRIS data to model fire temperature and background for the 2003 Simi Fire. The estimated fire temperature and land cover classifications were consistent with known patterns of fire behavior and vegetation distribution. Koetz et al. [38] used inversion of radiative transfer models to map spatially distributed fuel moisture content and fuel properties, serving as input for forest fire spread and mitigation models.

B. *Invasive species mapping*

Biological invasion is becoming a significant threat to global biodiversity and ecosystem preservation. Some invasive species could change the structure and /or functioning of the ecosystems where the invasion occurs [16]. Compared to multi-spectral remote sensing, which can only detect invasions when the invaders become dense and widespread, hyperspectral data with the capability of estimating canopy chemistry and structural properties, offers an enhanced potential for analyzing ecosystem changes caused by invasion in the early stages. This would lead to more effective management of invasive species [39]. The study by Underwood et al. [39] using AVIRIS imagery achieved high mapping accuracy for identifying the presence or absence of iceplant (97%). Asner and Vitousek

[16] used AVIRIS and a radiative transfer model to map canopy chemistry (nitrogen and water content) and determined the effects of invasion.

C. Contribution to Kyoto Protocol information products

Hyperspectral remote sensing can be used to generate some Kyoto Protocol information products. The Carbon Budget Model (CBM-CFS2) is the primary system used by the Canadian Forest Service (CFS) to describe the dynamics of species groups and assess the status of carbon distributions in Canada's forests [40]. The input data for the model are from provincial forest inventories, and growth curves from temporary and permanent sample plots. The more accurate forest classifications from hyperspectral remote sensing improve the accuracies in forest inventories which lead to more accurate estimates produced by the CBM-CFS2 model. Another contribution is that forest biomass, aboveground carbon, afforestation, reforestation, and deforestation (ARD) can be estimated directly from remote sensing imagery [41]. These can be used to compare and validate the modeled biomass, carbon, and change products. The Kyoto Protocol products from hyperspectral remote sensing and the CBM-CFS2 model with more accurate forest information would help countries, such as Canada, to meet the reporting commitments on the sustainability of their forest resources.

D. Monitoring forest health

Information in forest canopy biochemical composition obtained with high accuracy from hyperspectral data can also be used to monitor forest health. Goodenough et al. [30] have developed bioindicators for mapping chlorophyll, nitrogen, moisture content, and thus stress as derived from hyperspectral data. With the AVIRIS data, nitrogen content of a coniferous forest was predicted with a R^2 of 0.82. Moisture content was the most difficult to map and required the use of multiple models. The chemical maps provide valuable input into sustainable forest management. The presence or absence of specific biochemicals can help determine forest health and productivity. Further refinement of existing models also helped to assess multiple stress responses in Norway spruce trees, taking into account within crown variability. The radiative transfer inversion was constrained using a pre-classification approach based on plant ecophysiological parameters, allowing the detection of processes such as regeneration at unprecedented accuracies [42].

E. Global change studies

The atmospheric CO_2 concentration began to increase from the end of the 18^{th} century [43]. Land ecosystems play an important role in the global carbon cycle. Mapping the vegetation growth and distribution is critical for understanding the feedbacks between land ecosystem and atmospheric CO_2. The study [43] used remote sensing data to analyze the CO_2 fertilization effects on vegetation. It demonstrated how remotely sensed data can be used to investigate the effects of global change. Goetz et al. [44] analyzed the photosynthetic activity using remote sensing imagery across boreal North America over 22 years (1981 through 2003). They found that tundra vegetation has increased with rising CO_2 and temperature over the 22 years. In contrast, the interior forests areas do not have such a response, possibly due to drought stress, nutrient limitation, insect and disease damage, or changes in resource allocation. They also pointed out that different plant types should not be expected to respond similarly to environmental change. Therefore, information products (such as forest species, biophysical and biochemical features) from hyperspectral data and their changes over time can be used for climate change studies.

V. CONCLUSIONS

This article has summarized the land ecosystem products derived from hyperspectral data in particular combined with canopy radiative transfer models. The case studies were able to demonstrate the capability of hyperspectral data in: 1) classifying forest species more accurately than multi-spectral data; and 2) estimating biophysical and biochemical properties to higher accuracies. The applications of these products to which hyperspectral sensors have the greatest contribution, include products for forest disaster detection, invasive species mapping, Kyoto Protocol information products, monitoring forest health, and global change studies.

Canada has 10% of the world's forests and sells $80 billion in forest products annually [30]. The forest information products from hyperspectral data can be used to improve forest inventory, to detect areas of forest stress, and to support the application of nitrogen fertilization. Improvements in forest information can lead to very large benefits (>$700 M) for Canada's forest sector [8]. Canada is planning to build and launch the Hyperspectral Environment and Resource Observer (HERO) satellite in 2011. This satellite, jointly with the recently approved German ENMAP program, as well as promising hyperspectral sensor based mission proposals such as NASA's Flora mission and SpectraSat, CHRIS II on PROBA III, ESA FLEX amongst others will benefit land ecosystem applications in general and forestry in particular.

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