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Leaf chlorophyll content retrieval from airborne hyperspectral remote sensing imagery

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ABSTRACT

Hyperspectral remote sensing has great potential for accurate retrieval of forest biochemical parameters. In this paper, a hyperspectral remote sensing algorithm is developed to retrieve total leaf chlorophyll content for both open spruce and closed forests, and tested for open forest canopies. Ten black spruce (*Picea mariana* (Mill.)) stands near Sudbury, Ontario, Canada, were selected as study sites, where extensive field and laboratory measurements were carried out to collect forest structural parameters, needle and forest background optical properties, and needle biophysical parameters and biochemical contents chlorophyll *a* and *b*. Airborne hyperspectral remote sensing imagery was acquired, within one week of ground measurements, by the Compact Airborne Spectrographic Imager (CASI) in a *hyperspectral mode*, with 72 bands and half bandwidth 4.25–4.36 nm in the visible and near-infrared region and a 2 m spatial resolution. The geometrical–optical model 4-Scale and the modified leaf optical model PROSPECT were combined to estimate leaf chlorophyll content from the CASI imagery. Forest canopy reflectance was first estimated with the measured leaf reflectance and transmittance spectra, forest background reflectance, CASI acquisition parameters, and a set of stand parameters as inputs to 4-Scale. The estimated canopy reflectance agrees well with the CASI measured reflectance in the chlorophyll absorption sensitive regions, with discrepancies of 0.06%–1.07% and 0.36%–1.63%, respectively, in the average reflectances of the red and red-edge region. A look-up-table approach was developed to provide the probabilities of viewing the 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, the 4-Scale model was inverted to estimate leaf reflectance spectra from hyperspectral remote sensing imagery. Good agreements were obtained between the inverted and measured leaf reflectance spectra across the visible and near-infrared region, with R^2 = 0.89 to R^2 = 0.97 and discrepancies of 0.02%–3.63% and 0.24%–7.88% in the average red and red-edge reflectances, respectively. Leaf chlorophyll content was estimated from the retrieved leaf reflectance spectra using the modified PROSPECT inversion model, with R^2 = 0.47, RMSE = 4.34 μg/cm^2, and jackknifed RMSE of 5.69 μg/cm^2 for needle chlorophyll content ranging from 24.9 μg/cm^2 to 37.6 μg/cm^2. The estimates were also assessed at leaf and canopy scales using chlorophyll spectral indices TCARI/OSAVI and MTCI. An empirical relationship of simple ratio derived from the CASI imagery to the ground-measured leaf area index was developed (R^2 = 0.88) to map leaf area index. Canopy chlorophyll content per unit ground surface area was then estimated, based on the spatial distributions of leaf chlorophyll content per unit leaf area and the leaf area index.

1. Introduction

Monitoring forest health and stress from remotely sensed images is of concern for forest management. Spectrally continuous hyperspectral remote sensing data can provide information on forest biochemical contents, which are important for studying vegetation stress, nutrient cycling, productivity, and species recognition etc. (Asner et al., 1998; Curran, 1994; Davidson et al., 1999; Lewis et al., 2001; Noland et al., 2003; Sampson et al., 2003; Zarco-Tejada et al., 2004a,b). Healthy and stressed vegetations present different reflectance features in the green peak and along the red-edge due to changes in pigment levels (Belanger et al., 1995; Carter, 1994; Gitelson et al., 1996; Rock et al., 1988). Leaf chlorophyll content is the main parameter determining leaf spectral variation in the visible regions. Quantitative estimates of leaf chlorophyll content from hyperspectral data can provide a useful means for assessing forest growth and stress as affected by insects and diseases (Sampson et al., 2003). Total leaf chlorophyll content, and the ratio of chlorophyll *a* to *b* decrease when

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vegetation is under stress (Fang et al., 1998). The dependence of spectra on leaf biochemical properties provides the physical bases for remote detection of vegetation stresses through monitoring the change of chlorophyll content. Hyperspectral remote sensing with high spatial resolution has been demonstrated to be useful for detecting tree stress due to insect attack (Lawrence & Labus, 2003).

Empirical relationships between spectral indices and chlorophyll content measurements have been exploited for estimating leaf chlorophyll content. At the leaf level, optical indices have been widely used for plant species discrimination (Belanger et al., 1995), leaf vigor evaluation (Luther & Carroll, 1999), vegetation stress assessment (Carter, 1994; Gitelson & Merzlyak, 1996; Rock et al., 1988), and leaf chlorophyll estimation (Datt, 1998, 1999). le Maire et al. (2004) summarizes the chlorophyll spectral indices published until 2002. Most spectral indices employ ratios of narrow bands within spectral ranges that are sensitive to chlorophylls to those not sensitive and/or related to some other controls on reflectance. This method solves the problem of overlapping absorption spectra of different pigments, the effects of leaf surface interactions, and leaf and canopy structure (Chappelle et al., 1992; Peñuelas et al., 1995). Though spectral indices provide non-destructive, efficient, and sensitive measurements of leaf pigment contents from leaf spectral reflectance, these optical indices are generally developed for a specific species. As the size, shape, surface, and internal structure of leaves may vary from species to species, the application of optical indices to other vegetation types or biomes needs to be re-investigated. Efforts have been made to improve the robustness and generality of chlorophyll indices by testing over a range of species and physiological conditions. Nevertheless, spectral indices need calibration when applied to a specific species.

Statistical estimation of canopy-level biochemical contents is performed through different methods. The simplest way is to directly develop statistical relationships between ground-measured biochemical contents and canopy reflectance measured in the field or by airborne or satellite sensors (Curran et al., 1997; Johnson et al., 1994; Matson et al., 1994; Zarco-Tejada & Miller, 1999). Alternatively, some leaf-level relationships between optical indices and pigment content are directly applied to the canopy-level estimation (Peterson et al., 1988; Yoder & Pettigrew-Crosby, 1995; Zagolski et al., 1996). Canopy biochemical composition depends strongly on plant species as well as on canopy structure. Confounding factors that influence the remotely sensed optical properties make it difficult to spatially and temporally extrapolate leaf-level relationships to canopy-level. From the leaf to the canopy scale, the complicated perturbations of canopy structure to light transfer need to be carefully considered. Statistical relationships are often site- and species-specific, and thus cannot be directly applied to other study sites since the canopy structure and viewing geometry may vary from different sites and species.

Considerable progress has been made in physically based modeling approaches to estimate leaf biochemical contents. At the leaf level, numerical inversion of leaf-level radiative transfer (RT) models, such as PROSPECT and LEAFMOD, have been used to predict leaf chlorophyll content (Demarez et al., 1999; Ganapol et al., 1998; Jacquemoud & Baret, 1990; Renzullo et al., 2006; Zarco-Tejada et al., 2001). Studies using coupled leaf and canopy RT models attempt to understand the effects of controlling factors on leaf reflectance properties at the canopy scale (Demarez & Gastellu-Etchegorry, 2000). Canopy reflectance models are used to scale up the leaf-level relationship between optical indices and pigment content (Zarco-Tejada et al., 2001). Canopy RT models or ray-tracing models are also coupled with leaf RT models for pigment content retrieval (Dawson et al., 1997; Demarez & Gastellu-Etchegorry, 2000; Jacquemoud et al., 1995; Moorthy et al., in press; Zarco-Tejada et al., 2004a,b). Coupled models refine the development of spectral indices, which are insensitive to factors such as canopy structure, illumination geometry, and background reflectance for estimating foliar chlorophyll concentrations from canopy reflectance (Broge & Leblanc, 2000; Daughtry et al., 2000).

Canopy RT models often assume that a canopy is composed of horizontal, homogeneous vegetation layers with infinite extent and Lambertian scatterers. Elements of the canopy are assumed to be randomly distributed in space as a turbid medium (Liang & Strahler, 1993; Verhoef, 1984; Verstaete et al., 1990). It is suitable for close and dense canopies such as corn, soybean, and grass canopies where the foliage spatial distribution is close to randomness. At the canopy scale, especially for the heterogeneous, open, and clumped forest canopies, canopy structural effects on remote sensing signals are considerable. As remote sensing signals originating from vegetated surfaces are determined by both canopy structure and leaf optical properties, the structural effects in open forests cannot be ignored. Canopy RT models do not consider canopy architecture, they are valid only for closed canopy with high LAI (LAI>3) (Zarco-Tejada, 2000). Efforts have been made to deal with canopy structural effects on the retrieval of forest biochemical parameters. Zarco-Tejada et al. (2001) estimate leaf chlorophyll content through coupled leaf and canopy-level RT models using the red-edge index as a merit function to minimize the effects of forest canopy structure, shadows, and openings. The application of the method was extended to coniferous forests for scaling leaf-level pigment estimation to canopy-level using high spatial resolution airborne imagery to select only bright-crown pixels in the scene for analysis (Moorthy et al., in press; Zarco-Tejada et al., 2004a). Though this method produces promising results for leaf chlorophyll content retrieval, the structural effects imposed by the open forest canopies are not tackled. In cases where a pixel is completely occupied by sunlit foliage and the shadow effects are small, such a bright-crown methodology would be successful. However, remote sensing pixels, even at sub-meter resolutions, generally contain both sunlit and shaded fractions. For retrieving leaf-level information from remote sensing measurements above conifer forests which are generally open and have distinct structural effects, new methodologies are yet to be developed. It is highly desirable to develop a methodology that is applicable to not only closed but also open canopies.

For retrieving leaf-level information from canopy-level measurements, the interactions of radiation with plant canopies need to be considered. Models based on radiosity (Borel et al., 1991; Goel et al., 1991), and ray tracing (Gastellu-Etchegorry et al., 1996; Myneni et al., 1990) can simulate the complexity of multiple scattering, but simplifications of the mathematical and canopy architectural descriptions are inevitable due to computational limitations (Gastellu-Etchegorry et al., 1996; Thompson & Goel, 1999). Geometrical–Optical (GO) models combine the advantages of simplicity, easy implementation, and capability of simulating the effects of canopy structure on the single and multiple scattering processes (Chen & Leblanc, 2001). GO models use geometrical shapes, such as cones for conifers and spheres or spheroids for deciduous trees, to simulate the angular and spatial distribution patterns of reflected solar radiance from forests (Chen & Leblanc, 1997; Li & Strahler, 1988; Li et al., 1995). When considering the complex canopy architectural conditions, Geometrical–Optical-Radiative Transfer (GO-RT) models seem to be a good solution to solve the multiple scattering issues, in which geometrical optics are used to describe the shadowing (the first order scattering) effects, and RT theories are adopted to estimate the second and higher order scattering effects. Chen and Leblanc (1997) developed the 4-Scale model using geometrical–optical theories. The applicable scale can range from leaves, whorls, crowns, and stands to the landscape. It is appropriate for analyzing surface scattering and scene compositions, and suitable for non-dense canopies for the study of structural change (Peddle et al., 2003), directional reflectance (Leblanc et al., 1999), forest structural parameters (Chen et al., 2005), and forest background information (Canisius & Chen, 2007).

The purpose of this paper is to develop a hyperspectral remote sensing algorithm for retrieving leaf chlorophyll content. The specific objectives are: (i) to investigate the feasibility of GO-RT models for retrieving leaf chlorophyll content of closed and, in particular, open