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Bayesian estimation of seasonal course of canopy leaf area index from hyperspectral satellite data

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ABSTRACT

In this paper, Bayesian inversion of a physically-based forest reflectance model is investigated to estimate of boreal forest canopy leaf area index (LAI) from EO-1 Hyperion hyperspectral data. The data consist of multiple forest stands with different species compositions and structures, imaged in three phases of the growing season. The Bayesian estimates of canopy LAI are compared to reference estimates based on a spectral vegetation index. The forest reflectance model contains also other unknown variables in addition to LAI, for example leaf single scattering albedo and understory reflectance. In the Bayesian approach, these variables are estimated simultaneously with LAI. The feasibility and seasonal variation of these estimates is also examined. Credible intervals for the estimates are also calculated and evaluated. The results show that the Bayesian inversion approach is significantly better than using a comparable spectral vegetation index regression.

1. Introduction

Remote sensing of forest biophysical parameters, such as canopy leaf area index (LAI), has traditionally utilized data with low spectral resolution (i.e. multispectral measurements). Hyperspectral measurements (imaging spectroscopy) offer finer-grained spectral and radiometric information on the environment. Yet, the use of hyperspectral satellite measurements in estimation of forest parameters has been hampered by the larger data dimension compared to multispectral data and the relatively low number of operational hyperspectral satellite sensors. Several new satellite missions providing high spectral resolution data will be launched in the forthcoming years (including, for example, the EnMAP and PRISMA missions). Therefore, there is an urgent need to develop more efficient analysis methods to tackle the problem of high data dimensions.

Most of the existing methods for estimation of canopy LAI from hyperspectral measurements use only a few select spectral bands and thus do not utilize the full information content of the remotely sensed measurements. Of the existing approaches, empirical regression using narrowband vegetation indices (VI) has been the most widely studied [e.g. 3,6,10]. The primary drawback of empirical VI regression is its high site, time and species specificity: a regression model trained in one forest area usually does not generalize well to other locations. In theory, approaches based on forest reflectance model inversion can overcome this problem. While studies using reflectance model inversion with hyperspectral measurements have been done using airborne hyperspectral sensors and either band selection [17,22] or the full hyperspectral measurement [1], studies using the inversion approach with spaceborn sensors are still either scarce or nonexistent.

Recently, Varvia et al. [27] proposed a Bayesian method to estimate canopy LAI from hyperspectral satellite measurements. The method is based on Bayesian inversion of a physically-based forest reflectance model. The simulation results in [27] indicated improved estimation accuracy compared to the empirical vegetation index regression approach. Main advantages of the new method are that it also allows simultaneous estimation of other forest reflectance model parameters, such as leaf albedo, and produces uncertainty estimates for the model variables. In this article, the Bayesian approach is tested using EO-1 Hyperion satellite data in a Finnish boreal forest. The method is compared to a conventional VI regression using both field-measurements and reflectance model simulations as a training data. The performance of the uncertainty estimates produced by the Bayesian method is also evaluated. Moreover, the seasonal dynamics of the estimated LAI, leaf albedo and understory reflectance are examined.

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Table 1
A summary of study stands.

	Coniferous	Broadleaved
Number of stands	11	7
Mean tree height (m)	7.5 – 18.6	11.7 – 23.1
Stem volume ($m^3 ha^{-1}$)	40 – 220	71 –243
LAI_{eff} (May)	1.5 – 3.6	0.7 – 1.5
LAI_{eff} (June)	1.3 – 4.3	2.2 – 3.1
LAI_{eff} (July)	1.8 – 4.6	2.6 – 3.4

2. Materials and methods

2.1. Study area

The study area is located next to Hyytiälä Forestry Field Station in southern Finland (6150' N, 2417' E). Dominant tree species in the area are Norway spruce (*Picea abies* (L.) Karst.), Scots pine (*Pinus sylvestris* L.) and birches (*Betula pubescens* Ehrh., *Betula pendula* Roth.). Understory vegetation is usually composed of two layers: a ground layer of mosses and lichens, and an upper understory layer which has dwarf shrubs, graminoids, and/or herbaceous species. The greening of vegetation after the winter starts in early May, peak growing season is typically reached by late June and the vegetation stays relatively stable until mid-August.

2.2. Field measurements

For this study, we used data from 18 stands which represented different species compositions and age classes (stand age varied from 25 to 100 years) typical to the region. Canopy gap fractions and effective leaf area index (LAI_{eff}) of all the plots were measured in early May, early June and early July in 2010 (which coincide with the acquisition of Hyperion images, see Section 2.3 and Table 1). The measurements were carried out in exactly the same locations using two units of the LAI-2000 Plant Canopy Analyzer (Li-Cor Inc.) to obtain simultaneous readings from above and below the canopy. The instrument's optical sensor measures diffuse sky radiation (320– 490 nm) in five different zenith angle bands (centered at zenith angles: 7°, 23°, 38°, 53° and 68°). Simultaneous measurements with two LAI-2000 PCA units provide canopy transmittances (i.e. canopy gap fractions) for five zenith angles which can then be used to generate LAI based on inversion of Beer's law [28]. A total of twelve points per stand were measured according to a standard VALERI network (Validation of Land European Remote Sensing Instruments) sampling design [see e.g. 14]. The measurement points were located as a cross and placed at four-meter intervals on a North-South transect (6 points) and on an East-West transect (6 points). The below-canopy measuring height was 1 m above the ground i.e. only trees were included in the field-of-view. The LAI-2000 measurements were made during standard overcast sky conditions or during clear sky conditions in late evening and early morning when the Sun was below the field-of-view of the LAI-2000 instrument's optical sensor. The measurements are described in more detail in Heiskanen et al. [7].

Concurrently with the LAI measurements, data on understory reflectance spectra was collected in four stands representing common site fertility types: mesic, xeric, sub-xeric and herb-rich sites. In each of the four sites, a 28-m long transect was measured at 70 cm intervals under diffuse light conditions using a FieldSpec Hand-Held UV/VNIR (325 – 1075 nm) Spectroradiometer manufactured by Analytical Spectral Devices (ASD). No fore-optics were attached to the instrument which means that the field-of-view was 25°. The raw measurement data were processed to hemispherical-directional reflectance factors (HDRF) and averaged for all measurement points in each transect. The measurements and data are described in more detail by Rautiainen et al. [20].

In addition, we had access to regular stand inventory data which had been collected in all our study plots a year before the satellite images were acquired. In this study, the forest inventory data are used only to provide background information on site fertility type, stand structure and species composition (Table 1).

2.3. Satellite data

Three EO-1 Hyperion satellite images were acquired from our study area concurrently with the field data collection (Table 2). Hyperion was a narrowband imaging spectrometer onboard NASA's Earth Observing-One (EO-1) with 242 spectral bands (356 – 2577 nm) and a 30 m × 30 m spatial resolution [18]. The set of Hyperion images captures the main phenological changes occurring in the study area in 2010: the image from May corresponds to the time of bud burst, the image from June to the full leaf-out situation, and the image from July to the time of maximal leaf area.

First, striping in the Hyperion images (originally accessed as L1B products) was removed using spectral moment matching [25] and corrected for missing lines using local destriping methods [4]. The spectral smile was corrected for in standard method using interpolation and pre-launch calibration measurements [2]. Finally, the Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes (FLAASH) algorithm was used for atmospheric correction of the images [16]. The end product of the atmospheric correction process was hemispherical-directional reflectance factor (HDRF). More details on the preprocessing of this set of Hyperion images is available in [6]. The Hyperion images were georeferenced using approximately 20 ground control points. The mean HDRFs for each study stand were extracted using a 3 × 3 pixel window which corresponds to the area covered by the field measurements in each stand.

3. Bayesian estimation of effective LAI

In this section, the Bayesian approach to LAI estimation is shortly summarized. Except for slight adjustments in certain hyperparameters, the methodology is identical to Varvia et al. [27] and the reader is referred there for more detail.

The forest reflectance spectrum is modeled is adopted from Rautiainen and Stenberg [21]; in this so-called PARAS model, the bidirectional reflectance factor (BRF, $r(\theta_1, \theta_2, \lambda)$) of the forest for solar zenith angle θ_1, viewing angle θ_2, and wavelength λ is:

$$r(\theta_1, \theta_2, \lambda) = \rho_g(\theta_1, \theta_2, \lambda) t_c(\theta_1) t_c(\theta_2) + Q i_c(\theta_1) \frac{\omega_L(\lambda) - p\omega_L(\lambda)}{1 - p\omega_L(\lambda)}, \quad (1)$$

where ρ_g is the BRF of the understory layer, t_c is the canopy transmittance, $i_c = 1 - t_c$ the canopy interceptance, Q the approximative portion of upwards scattered radiation from the canopy [13], ω_L the leaf single scattering albedo, and p is the photon recollision probability, defined as the probability that a photon scattered in the canopy will interact within the canopy again [8,9]. It should be noted that the satellite measurements correspond to the hemispherical-directional reflectance factor (HDRF), which is approximated here using BRF under the implicit assumption that the incoming diffuse sky radiation is negligible compared to the direct sun component.

The wavelength dependent variables ω_L and ρ_g are approximated using splines following Varvia et al. [27]:

$$\omega_L = S(\lambda; \tilde{\lambda}, \tilde{\omega}_L), \quad (2)$$

$$\rho_g = S(\lambda; \tilde{\lambda}, \tilde{\rho}_g), \quad (3)$$