Physically-based retrievals of Norway spruce canopy variables from very high spatial resolution hyperspectral data

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Abstract
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Physically-based retrievals of Norway spruce canopy variables from very high spatial resolution hyperspectral data

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Abstract—This study was conducted to answer two research questions: (1) what is the spatial variability of the leaf optical properties between 400–1600 nm (hemispherical-directional reflectance, transmittance, absorption) within young Norway spruce crowns, and (2) how to design a suitable physically-based approach retrieving the total chlorophyll content of a complex coniferous canopy from very high spatial resolution (0.4 m) hyperspectral data? It was proved that sun exposed needles of current age-class statistically differ (q-level = 0.01) from rest of the needles in reflectance between 510–760 nm. Last four age-classes of sun exposed needles were also found to be significantly different from almost all age-classes of sun shaded needles in transmittance from 760-1350 nm. An operational estimation of chlorophyll a+b content (C_{ab}) from an airborne AISA Eagle hyperspectral image was proposed by means of a PROSPECT-DART inversion employing an artificial neural network (ANN). A spatial pattern of estimated C_{ab} was successfully validated against the C_{ab} map produced by a vegetation index ANCB650-720. Coefficients of determination (R^2) between ground measured and retrieved C_{ab} were 0.81 and 0.83, respectively, with root mean square errors (RMSE) of 2.72 \mu g cm^{-2} for ANN and 3.27 \mu g cm^{-2} for ANCB650-720.

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I. INTRODUCTION

Physically-based retrieval of vegetation characteristics from optical remote sensing data of very high spatial resolution (pixel size ≤ 1 m) has, on one hand, the advantage of providing detailed spatial information. On the other hand such a retrieval has strong requirements in terms of: (1) image pre-processing (i.e., geometric, radiometric, and atmospheric corrections of the airborne/satellite raw data), (2) radiative transfer (RT) modeling (i.e., the RT model must be capable of handling the complexity of heterogeneous scenes with a very high 3D spatial resolution), (3) collection of representative optical and geometrical ground measurements for a reliable parameterization of the RT models and quality assessment of the results, and (4) selection of suitable algorithms to retrieve the desired vegetation parameters with high accuracy.

This paper illustrates the last two issues using as the modeling ecosystem a montane Norway spruce (Picea abies (L.) Karst.) forest. A representative optical parameterization of RT models in this kind of canopy needs an appropriate sampling strategy. Therefore, a first objective of this study was to investigate spectral differences in Norway spruce leaf optical properties between 400 and 1600 nm. Needles of four age-classes and three different irradiation conditions (sun exposed (E), transitional (T), and sun shaded (S)) were included in this investigation. The second objective was to introduce a physically based approach to retrieve quantitative variables, in particular total chlorophyll a+b content (C_{ab}), of a complex spruce canopy from very high spatial resolution (0.4 m) hyperspectral data. The motivation for this aim was to create map of canopy C_{ab}, which in turn could serve as a reference to validate satellite-based chlorophyll products.

II. MATERIAL AND METHODS

A. Study site

A young (28 years old) forest stand of Norway spruce trees, located at the permanent experimental research site Bily Kriz (the Moravian-Silesian Beskydy Mountains, Czech Republic; 18.54°E, 49.50°N; altitude 936 m above sea level), was selected as study site. The average annual air temperature at this stand is about 5.5°C, the average annual precipitations is between 1000 and 1400 mm. This regularly spaced plantation was established with three years old spruce seedlings in 1981. In 2006, the spruce stand contained about 1438 trees per hectare with a mean height of about 12 m, and an average diameter at breast height (DBH) of about 14 cm.

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B. Measurements and analyses of leaf optical properties

The leaf (needle) optical properties, i.e. hemispherical-directional reflectance, transmittance, and absorbance, between 400-1600 nm were measured using an ASD FieldSpec Pro spectroradiometer (Analytical Spectral Devices, Inc., USA) connected to the Li-Cor integrating sphere Li-1800-12 (Li-Cor, Inc., USA) according to the methodology published in [1]. Needle samples of last four age-classes (C – current year, C+1 – one year, C+2 – two years, and C+3 – three years old) were collected from a sun exposed (3rd whorl of branches), a transitional (around 5th whorl of branches), and sun shaded (below 7th whorl of branches) crown part of ten selected trees. In total 120 samples were gathered and measured during second week of September 2006. All the samples were analyzed in laboratory to obtain their total content of chlorophyll a+b, carotenoids, water, and dry biomass.

Statistically significant differences (α-level = 0.01) in intensity of the needle’s optical properties between 400-1600 nm were investigated using a two-way analyses of variance (ANOVA) and the Tukey multiple comparison test.

C. Hyperspectral airborne images and ground truth

A joint airborne/field campaign was carried out at the study site in September 18th, 2004. The hyperspectral image data with pixel size of 0.4 m, 64 spectral bands, and Full-Wide-Half-Maximum (FWHM) of about 10 nm were acquired with an aerial VNIR system AISA Eagle (SPECIM, Ltd., Finland). The transformation of digital numbers into radiant as well as the orthorectification and projection of data into the UTM Zone 34N were done using the CaliGeo software. The atmospheric and the across-track brightness gradient correction were carried out in the ATCOR-4 model [2]. A subset covering the whole study area (about 200 by 320 m) was extracted from the AISA Eagle hyperspectral image and classified using a maximum likelihood rule. Following three classes were identified: background, sunlit canopy, and shaded canopy. Sunlit and shaded canopy pixels were used to compute the canopy cover (CC) of the observed spruce stand. However, only the reflectance recorded in sunlit canopy pixels was used in the C_ab retrieval. This should ensure a high quality (noiseless) signal.

In total 120 needle samples were from nine spruce crowns were analyzed to create the C_ab reference data. The representative C_ab values were computed per sampled crown using a C_ab average weighted by the irradiance conditions of the horizontal crown levels and by the relative abundance of the age-classes within each crown.

D. PROSPECT-DART radiative transfer modeling

The leaf radiative transfer model PROSPECT [3], adjusted for Norway spruce needles [1], was coupled with the three dimensional (3D) Discrete Anisotropic Radiative Transfer (DART) model [4] to simulate hyperspectral images of the Norway spruce scene under investigation. PROSPECT inputs C_m (dry matter content; C_m = 0.0118-0.0233 g cm^-2) and C_w (water content; C_w = 0.0365-0.0486 cm) were measured on the needle samples collected for the chlorophyll analysis. The structural parameter N was retrieved from reflectance and transmittance measurements of needles (N = 2.02-2.08). The free variable, chlorophyll content (C_ab), was varying between 10-85 μg cm^-2 according to a priori knowledge (Tab.1).

PROSPECT-DART key variables had to be parameterized so that the simulated hyperspectral images captured the optical and geometrical variabilities of the investigated canopy. Most of the DART inputs were collected during the airborne/field campaign. Only some additional allometric parameters on tree crown architecture were obtained from previous observations of the same test site [5]. 3D mock-ups, covering an area of 6 by 6 m, were constructed using four (CC = 75%), five (CC = 85%), and six (CC = 95%) spruce trees in case of a regular tree distribution and five (CC = 75%), six (CC = 85%), and seven (CC = 95%) trees in case of an irregular (clumped) stem distribution. Each Norway spruce crown (height between 9-11 m) was constructed out of 11 horizontal levels parameterized with specific average leaf angles (from 25° to 40°) and leaf optical properties. The leaf optical properties were simulated using the Norway spruce adjusted PROSPECT model, according to the observed proportion of the different needle age-classes. Destructive measurements were used to parameterize the vertical and horizontal distributions of foliage (spatially specific crown defoliation), the distribution of woody elements (DART uses superimposed parallelepipeds to represent trunks, and pyramids to represent branches that grow directly from the trunk), and the distribution of tiny woody twigs (DART uses turbid media to represent branches smaller than 1 cm in diameter). The forest stand background, covering a continuous slope of 13.5°, was modeled as a mixture of bare soil and needle litter. The optical properties of the additional scene surfaces (i.e., bark of trunks and branches, and forest background elements) were defined in DART as to be of Lambertian nature. The radiative transfer through the atmosphere above the forest stand was not included. Therefore, reflectance (the top of canopy bidirectional reflectance factor – BRF) of DART simulated spectral bands (Tab.1) corresponded to the atmospherically corrected AISA-Eagle BRF.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope</td>
<td>Deg.</td>
<td>13.5°</td>
</tr>
<tr>
<td>Sun angles</td>
<td>Deg.</td>
<td>θ_s = 47.8°, φ_s = 183.4°</td>
</tr>
<tr>
<td>Canopy cover</td>
<td>%</td>
<td>75, 85, 95</td>
</tr>
<tr>
<td>Leaf area index</td>
<td>m² m⁻²</td>
<td>4, 5, 6, 7, 8, 9</td>
</tr>
<tr>
<td>Chlorophyll content</td>
<td>µg cm⁻²</td>
<td>10, 25, 40, 55, 70, 85</td>
</tr>
<tr>
<td>Visible simulated bands</td>
<td>nm</td>
<td>652.1, 661.4, 670.7, 680.1, 689.4</td>
</tr>
<tr>
<td>NIR simulated bands</td>
<td>nm</td>
<td>698.7, 708.1, 717.4</td>
</tr>
</tbody>
</table>

E. Remote sensing retrieval methods

1) Artificial neural network (ANN): Several ANN architectures were tested using the neural network toolbox available in MATLAB®. A two-layer feedforward backpropagation neural network with a tan-sigmoidal transfer function in the first layer and a linear transfer function in the
output layer was selected for the analysis. The network was trained using the sunlit DART simulated crown pixels in the wavelength range from 650-720 nm, transformed by means of continuum removal [6]. Prior to the network training, the continuum removed BRF and the $C_{ab}$ data were pre-processed to have a zero mean and a standard deviation of 1. Designed ANN had six neurons in the first layer (one per input) and one neuron in the output layer ($C_{ab}$). The Levenberg-Marquardt optimization algorithm was selected to train the ANN using 108 DART scenes (50%). Remaining scenes were split for validation (25%) and testing (25%) purposes. The validation dataset was presented to the ANN simultaneously with the training dataset. When the error of the validation dataset was above a certain threshold then the network training was early stopped to prevent the ANN overfitting.

2) Chlorophyll vegetation index: The Area under curve Normalized to maximal Chlorophyll absorption Band depth between 650-720 nm (ANCB$_{650-720}$) is a variant of the optical index ANMB$_{650-725}$ described in detail in [7]. The only difference is that the ANCB$_{650-720}$ uses a shorter wavelength range (650-720 nm) and that normalization of the continuum removed area is done using the maximum chlorophyll absorption wavelength (in this case 670.7 nm). The ANCB$_{650-720}$ computed from the sunlit crown pixels of the DART images was statistically related to the input $C_{ab}$. The obtained equation was applied to the sunlit pixels of the AISA Eagle image to verify the consistency of the spatial distribution of $C_{ab}$ already retrieved by the ANN approach.

III. RESULTS AND DISCUSSION

A. Variability in Norway spruce optical properties

A visual comparison of the mean needle optical properties revealed unchanging reflectance and transmittance signatures of E and T samples of C+1, C+2, and C+3 age-classes in all investigated wavelengths. In the case of the S samples, the reflectance slightly decreased and transmittance increased (3-5%) in the green and the near infrared (NIR) parts except for C+3 needles where both optical properties remained stable. The largest variation in optical properties was found for the C needles. Their reflectance was systematically descending and their transmittance was increasing by means of 5% in green and almost 10% in NIR wavelengths due to the irradiation conditions changing from direct to diffuse sun light. This means that new C needles developed in different illumination conditions differ significantly not only in $C_{ab}$ (measured average $C_{ab}$ for E $\sim 1.5$ mg g$^{-1}$, T $\sim 2.3$ mg g$^{-1}$, S $\sim 3.3$ mg g$^{-1}$), but also in inner leaf structure and quantity/quality of the cell tissues. These results were supported by outcomes of applied statistical tests, which showed that C needles were different from the other age-classes in reflectance between 510-760 nm and absorption between 510-630 nm (the statistical significance $\alpha$-level of 0.01). Finally, all the investigated age-classes of E needles and older T needles (C+2 and C+3) were statistically different from almost all S age-classes in transmittance at 760-1350 nm.

B. Retrieval of Norway spruce canopy chlorophyll content

The results of the ANN training were satisfactory with $R^2$ equal to 0.9988 and root-mean-square-error (RMSE) equal to 0.40 $\mu$g cm$^{-2}$. Also the best fitting statistical relationship,

![Figure 1](image_url)氯酚含量（Cab）图，展示了在研究地点Bily Kriz（捷克共和国）从六根连续去除的AISA Eagle带用人工神经网络（ANN）在PROSPECT-DART模拟的高光谱场景中生成的sunlit挪威云杉冠层氯酚含量图。 (Projection UTM, 34 N).
The chlorophyll map produced by the ANN inversion of the PROSPECT-DART simulated scenes was found to be consistent with the results obtained for the ANCB650-720 index. The ground Cab measurements confirmed that the ANN method is suitable to retrieve Norway spruce canopy variables from very high spatial resolution hyperspectral data. The continuum removal transformation effectively compensate for potential residual differences in BRF caused by the PROSPECT-DART simulation and by the pre-processing of the AISA Eagle image. Therefore the use of continuum removed spectral bands improved the ANN performance. Nevertheless, pure vegetation reflectance was found to be a prerequisite for an accurate Cab estimation by means of both applied retrieving methods.

IV. CONCLUSIONS

This study has proved that optical properties of the first age-class needles are significantly different from the rest of the older needles. The most stable optical properties were observed for the four years old needles. Increasing needle adaptation to diffused irradiation was found to correspond with a decrease in reflectance and increase in transmittance (absorption remained almost constant). Sampling of only two irradiation zones (sun exposed and shaded) might be considered as sufficient in the case of young spruces. It is highly recommended to always sample needles of the current year (C). However, one randomly selected needle sample seems to be enough to properly characterize the optical properties of the C+1, C+2, and C+3 needle age-classes.

\[ \ln(C_{ab}) = 7.3903 - 7984.0135 / (ANCB650-720)^2, \]  

was highly significant with an R² of 0.9989. The map of C_{ab} estimated by the ANN retrieval is shown in Fig. 1. The spatial pattern of C_{ab} estimates produced by the ANCB650-720 index was quite similar (map not presented) with only differences in low C_{ab} values. As shown in Fig. 2c, the ANCB650-720 approach was less sensitive and consequently overestimating lower chlorophyll foliage concentrations (see also Fig. 2b). This was probably due to the exponential nature of the statistical relationship (1). Nevertheless, the RMSE computed between ANCB650-720 and ground measured C_{ab} references of nine needle age-classes.

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