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$ANMB_{650\text{-}725}$ – A NEW OPTICAL INDEX FOR CHLOROPHYLL ESTIMATION OF A FOREST CANOPY FROM HYPERSPECTRAL IMAGES

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ABSTRACT

Recent hyperspectral remote sensing allows retrieving the total chlorophyll (C_{ab}) concentration of vegetation using the appropriate optical indices, and/or by means of biochemical information, scaled up from leaf to canopy level within radiative transfer (RT) models. Plenty of chlorophyll optical indices can be found in literature for the leaf level, nevertheless only some of them were proposed for a complex vegetation canopy like a forest stand.

A new optical index named Area under curve Normalized to Maximal Band depth between 650-725 nm ($ANMB_{650\text{-}725}$) is proposed to estimate chlorophyll content of a Norway spruce (*Picea abies*, Karst.) forest stand. $ANMB_{650\text{-}725}$ is based on the continuum removal of the chlorophyll absorption feature at the red-edge part of the spectrum between wavelengths of 650-725 nm. Suitability of the index and sensitivity on disturbing factors was tested using a 3D Discrete Anisotropic Radiative Transfer (DART) model coupled with a leaf radiative transfer model PROSPECT adjusted for spruce needles. Results about the $ANMB_{650\text{-}725}$ abilities within a coniferous forest canopy were compared also with the performance of the chlorophyll indices ratio TCARI/OSAVI.

Test results, carried out with the DART model for hyperspectral data with 0.9 m pixel size, showed a strong linear regression of the $ANMB_{650\text{-}725}$ on spruce crown C_{ab} concentration (R^2=0.9798) and quite strong resistance against varying canopy structural features such as LAI and canopy closure. The root mean square error (RMSE) between real and the $ANMB_{650\text{-}725}$ estimated C_{ab} concentrations was only 9.53 $\mu g/cm^2$ while the RMSE generated from prediction of the TCARI/OSAVI was two times higher (18.83 $\mu g/cm^2$). Chlorophyll retrieval using the $ANMB_{650\text{-}725}$ index remained stable also after introduction of two signal disturbing features, i/ 20% of the spectral information of epiphytic lichen (*Pseudevernia* sp.) regularly distributed within the spruce canopy, and ii/ simulation of higher sensor noise (computed for a signal to noise ratio equal to 5).

Keywords: hyperspectral quantitative remote sensing, chlorophyll optical index $ANMB_{650\text{-}725}$, DART, radiative transfer model.

INTRODUCTION

Current approaches of quantitative remote sensing allow to estimate the concentration of biochemical constituents, for instance total concentration of the chlorophyll *a* and *b* (C_{ab}), using fine spectral resolution (hyperspectral) image data in combination with radiative transfer models (1, 2, 3, 4). A number of optical indices have been proposed for estimation of leaf C_{ab} content (5), but not all of them are suitable to be used on the level of the forest canopy. A forest canopy is a spatially heterogeneous system, assembled from a certain amount of leaves and woody twigs (shoots in case of conifer species), branches of several orders, stems, and other components, arranged in the 3D space in a specific way. Therefore, any optical spectral index, for estimation of the biochemical parameter, should be driven by the concentration of the biochemical constituent, and be independent of the other structural and biochemical characteristics of the canopy (e.g. density and distribution of leaves, canopy closure, etc.) including surrounding environment (e.g. influence of understory and soil on background).

An ideal tool to design and test optical indices for retrieval of the biochemical properties appropriately are radiative transfer (RT) models. Therefore, combination of the RT models PROSPECT and DART (Discrete Anisotropic Radiative Transfer), was used in our study aiming to develop and test the sensitivity of a robust chlorophyll estimating optical index for a heterogeneous forest canopy. A newly proposed index named Area under curve Normalized to Maximal Band depth between 650-725nm ($ANMB_{650-725}$) is based on the method called continuum removal of reflectance spectra (4), using advantages of fine spectral resolution and sampling band interval of the hyperspectral images acquired with a very small pixel-size.

METHODS

DESIGN OF THE $ANMB_{650-725}$ INDEX

The new chlorophyll estimating optical index $ANMB_{650-725}$ is computed from the continuum removal of the chlorophyll absorption feature at the red-edge part of the spectrum, i.e. between the wavelengths of 650-725 nm. Increase in chlorophyll concentration causes deepening of the chlorophyll absorption feature at the red-edge of reflectance with the absorption maximum at approximately 680 nm (see figure 1a). The area under a continuum-removed reflectance curve from 650 to 725 nm is getting significantly smaller with chlorophyll decline, and the maximal band depth of this area is systematically changing too (see figure 1b). First, the continuum removal procedure (6) is applied on the vegetation hemispherical directional reflectance factor (HDRF) of wavelengths between 650 to 725 nm. Secondly, a maximal band depth (MBD) is searched within the used wavelengths, and the area under the continuum-removed reflectance curve (AUC) is integrated according to the equation:

$$\mathrm{AUC} = \frac{1}{2}\sum_{j=1}^{n-1}\left(\lambda_{j+1} - \lambda_j\right)\left(\rho_{j+1} + \rho_j\right), \quad (1)$$

where ρ_j and ρ_{j+1} are reflectance values at the *j* and *j*+1 bands, λ_j and λ_{j+1} are wavelengths of the *j* and *j*+1 bands, and *n* is number of the used spectral bands. Finally, the AUC is normalized to the MBD. Normalization of the AUC by the MBD is a crucial step ensuring a strong relationship between the $ANMB_{650-725}$ and the chlorophyll content at higher concentrations. The dependence relation of the AUC on the C_{ab} concentration saturates for C_{ab} > 60 $\mu g/cm^2$, while values of the MBD above this C_{ab} concentration start to systematically decrease. This disproportional non-linear relationship between the AUC and the MBD makes their ratio, i.e. the $ANMB_{650-725}$ index, sensitive to not only low and average, but also to high concentrations of C_{ab}.

RADIATIVE TRANSFER MODELS

Combination of the PROSPECT and DART models was used to simulate airborne very high spatial resolution hyperspectral images of a matured Norway spruce (*Picea Abies* (L.) Karst.) forest stand, and subsequently to generate the HDRF database of sunlit crown spectral signatures.

The PROSPECT model (7) simulates leaf spectral hemispherical reflectance and transmittance signatures from 400 to 2500 nm as a function of leaf structural parameters and leaf biochemical components. Scattering is described by a specific refractive index (n) and a parameter characterizing the leaf mesophyll structure (N). Absorption is modelled using pigment concentration (C_{ab}), water content (C_w), dry matter content (C_m) and the corresponding specific spectral absorption coefficients (k_{ab}, k_w, and k_m). PROSPECT was adjusted to simulate properly spectral properties of the Norway spruce needles by means of the measured leaf directional hemispherical optical, biochemical and structural characteristics (8). PROSPECT outputs were directly used in the DART model to simulate the hemispherical directional reflectance factor (HDRF) (9) at the top of the canopy (TOC).

DART is a 3D radiative transfer model, based on the discrete ordinance method and an iterative approach. A simulated landscape scene is represented as a rectangular solid medium of adjacent cells forming a 3D matrix. Each cell of the matrix is identified with the x, y and z coordinates at the centre point. Cells can create different types of scene elements, classified as opaque or solid cells (e.g. soil or water) and semi-opaque or turbid cells (e.g. leaves of vegetation), which can vary in spatial dimensions. Each of them requires a specific optical and structural characteristic, for instance leaf area index, leaf angle distribution, and reflectance and transmittance functions in case of vegetation foliage. The 3D radiation regime and the canopy HDRF are realistically generated by considering topography, major physical mechanisms (e.g. hotspot effect), surface optical properties and four types of scattering. A detailed description of the DART algorithm and functions is available in Gascon et al. (10), Gastellu-Etchegorry et al. (11), and Gastellu-Etchegorry et al. (12).

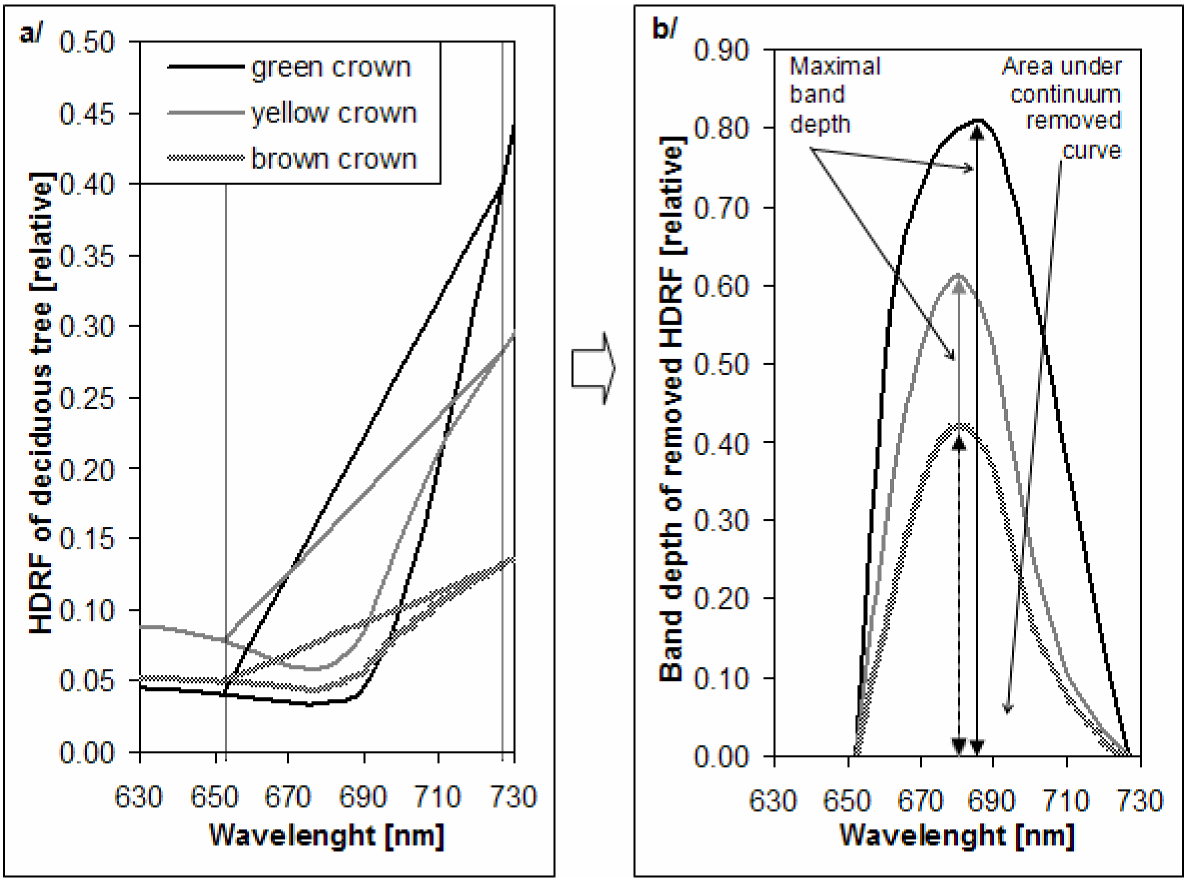

Figure 1: Description of continuum removal and band depth calculation to generate the ANMB$_{650-725}$ index from sunlit vegetation spectral signatures of a "green" (high C_{ab}), "yellow" (very low C_{ab}), and "brown" (dead tree without C_{ab}) coloured crown of a deciduous tree extracted from an AISA Eagle atmospherically corrected hyperspectral image: a/ delineation of the reflectance feature at the chlorophyll absorption between 650 and 725nm; b/ maximal band depth (MBD) and area under reflectance continuum removed curve (AUC).

PARAMETERIZATION OF THE RT MODELS AND GENERATION OF THE HDRF DATABASE

The RT models were parameterized using the data acquired during the field survey of the Norway spruce forest stands situated near the village Modrava (48°59'N, 13°28'E), at the Sumava Mts. National Park (Czech Republic), in September 2003. Heterogeneous representative 3D scenes of three canopy closures were generated out of averages and standard deviations of the tree field measurements. Clumping of the foliage within the branches was simulated as a combination of systematic and random propagation of the "gaps" (empty "air" cells) within the tree canopy. This calibration was based on the visual observation of the crown defoliation and laboratory destruction of 16 representative branches. Ground surface was represented by a flat surface (digital elevation model was not included) covered by the most frequent mountain grass *Calamagrostis villosa*. Mean allometric characteristics of the representative trees for the HDRF database simulation are described in table 1. Leaf optical properties were generated in the adjusted PROSPECT model as weighted averages of spectral properties of the last three needle generations (age weights were calculated from the branch destruction). 78 needle samples from 13 selected trees were analyzed in this respect to obtain the following average input values: C_w = 0.06 cm, C_m= 0.026 g/cm^2, N = 2.15.

Finally, 162 DART simulations were performed to obtain the top of canopy HDRF database of the virtual Norway spruce stands through all possible combinations of the following varying inputs: LAI (2, 3, 4, 5, 7 and 9), C_{ab} content (20, 30, 40, 50, 60, 70, 80, 90, 100 µg/cm^2), and % of canopy closure (CC) (35, 55, and 80%). The solar illumination direction was defined by the azimuth angle of 181.2°and zenith angle of 42.2° (real solar noon on September 15th). Outputs were simulating the hyperspectral images of the AISA airborne sensor (Specim, Ltd., Finland), having 17 spectral bands of 0.9 m spatial resolutions. In the final step only spectral signatures of sunlit crown pixels of appropriate spectral bands from 648-726 nm were extracted to build the HDRF database for the establishment of the $ANMB_{650-725}$ chlorophyll optical index.

Table 1: Universal tree characteristics used for building the HDRF database.

Length of trunk [m]		Trunk diameter [m]		Length of crown [m]	Crown radius [m]	
Outside of crown	Inside of crown	Outside of crown	Inside of crown		Lower part	Upper part
7.75	9.20	0.36	0.19	13.50	2.70	0.00

$ANMB_{650-725}$ VALIDATION AND SENSITIVITY ANALYSIS

Three real forest research plots, selected within the matured Norway spruce stands at the Sumava Mts. National Park, were modelled in the DART model for validation of the $ANMB_{650-725}$. DART landscape representatives were prepared using a FieldMap digital forest mapping system coupled with the Laser Rangefinder Impulse 200 and the MapStar electronic compass. Realistic scenes contained 13 sample trees, several neighbourhood adult and young trees, lying dead wood, and vegetation understory combined with litter of senescent spruce needles and bare soil. Directional hemispherical optical properties of major surfaces were measured by the Li-Cor spectroradiometer LI-1800-22 connected to an integrating sphere LI-1800-12. Structural parameters of the forest stands were set in a similar way as for the HDRF database scenes.

The total concentrations of the chlorophyll *a* and *b* (C_{ab}) for 99 collected samples of current, two and three year old needles were determined spectrophotometrically in the laboratory. A Unicam Helio α spectrophotometer (Helios alpha, Unicam Ltd., Cambridge, UK) was used according to the methodology of Porra et al. (13) and Wellburn (14) for this purpose. The proper needle age-class ratio of chlorophyll concentrations was up-scaled by the adjusted PROSPECT-DART model into the TOC HDRF AISA hyperspectral images of observed spruce stands. $ANMB_{650-725}$ was derived from spectral signatures of sunlit crown pixels of 13 sample trees. The equation of linear regression, established between $ANMB_{650-725}$ and C_{ab} concentration from the HDRF database, was applied to estimate their C_{ab} values. Finally, the root mean square error (RMSE) was computed between retrieved and true C_{ab} concentrations to assess the accuracy of the $ANMB_{650-725}$ estimation.

The performance of the $ANMB_{650-725}$ optical index was compared with C_{ab} prediction abilities of the optical ratio TCARI/OSAVI. Haboudane et al. (15) proposed the ratio of the Transformed Chlorophyll Absorption in Reflectance Index (TCARI) and the Optimized Soil-Adjusted Vegetation Index (OSAVI) (16) as strongly sensitive to chlorophyll concentration and highly resistant to the variations of LAI (Leaf Area Index) and solar zenith angle at the canopy level. The TCARI is a transformed variant of the chlorophyll index MCARI (Modified Chlorophyll Absorption in Reflectance Index) (17), and the OSAVI index belongs to the family of soil line vegetation indices (18).

Finally, a sensitivity analysis of the $ANMB_{650-725}$ C_{ab} predictability on the presence of epiphytic lichens within the canopy (scenario #1) and added sensor noise (scenario #2) was performed. Scenario #1 was realized by spectral mixing of the measured hemispherical optical properties of most common lichen at the Sumava spruce forests, *Pseudevernia* sp., with the original needle optical properties in ratio 1:4. Scenario #2 was simulated by adding a certain level of a detector noise to the simulated image of scenario #1. The noise simulated in this work resembled signal to noise ratio (SNR) equal to five, by simulating the noise of standard deviation approximately 20%.

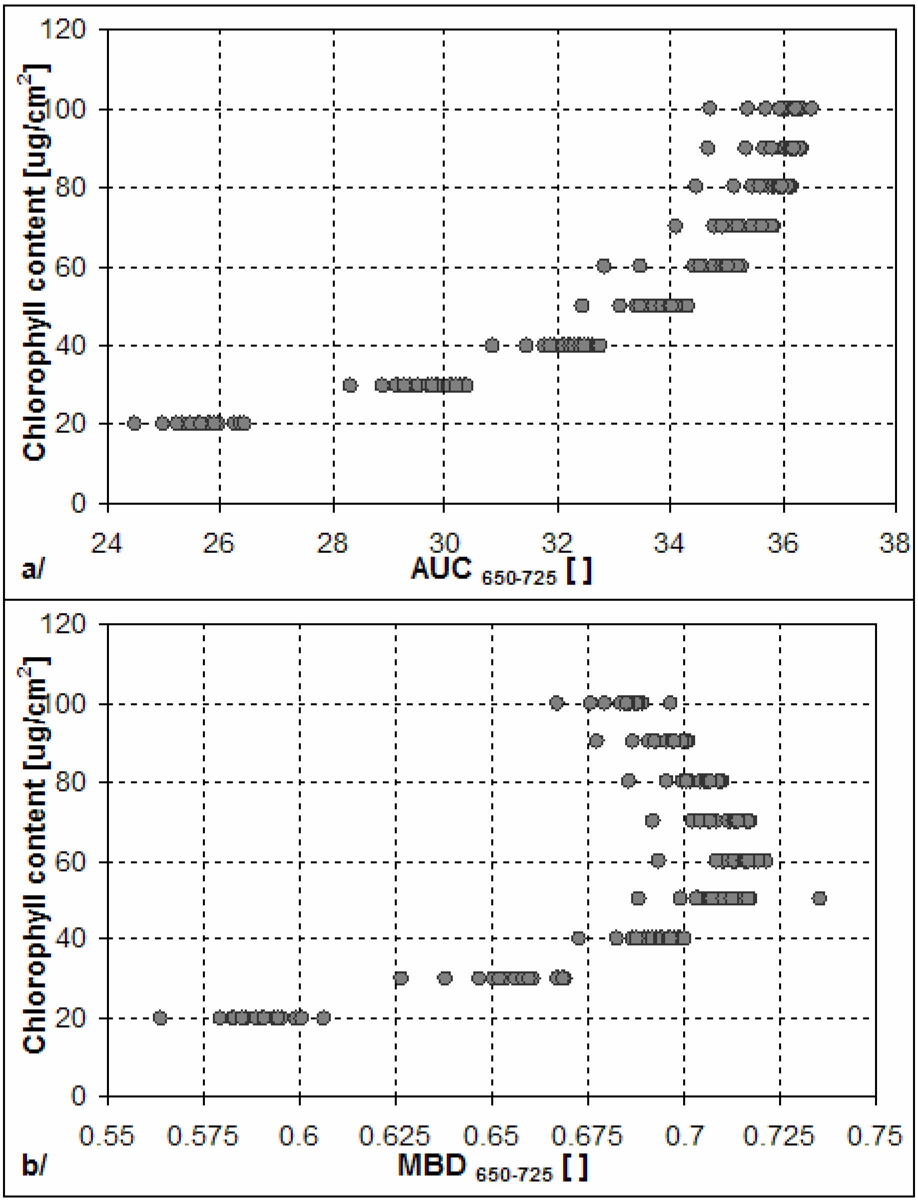

Figure 2. Relationship of the optical parameters and canopy chlorophyll concentration computed from the HDRF database: a/ Integrated area under continuum removed reflectance between 650-725 nm ($AUC_{650-725}$); b/ Maximal band depth of continuum removed reflectance between 650-725 nm ($MBD_{650-725}$).

RESULTS

Figure 2a shows the exponential relationship of the integrated area under continuum removed reflectance curve between 650-725 nm ($AUC_{650-725}$) and canopy chlorophyll concentration computed from the HDRF database. The $AUC_{650-725}$ values saturate for a C_{ab} concentration above 60 μg/cm^2 which means $AUC_{650-725}$ is not able to resolve a C_{ab} content higher than 60 μg/cm^2. On the other hand, the maximal band depth of continuum removed canopy reflectance between 650-725 nm ($MBD_{650-725}$) is steeply growing with an increase of the C_{ab} concentration up to 60 μg/cm^2, gains the maximal values at this C_{ab} concentration, and decreases for a C_{ab} content above 60 μg/cm^2 (figure 2b). Consequently, the proposed reciprocal ratio of these two optical parameters, named the $ANMB_{650-725}$ index, exhibits a strong linear relationship with the total canopy chlorophyll concentration. Variability in $ANMB_{650-725}$ due to varying LAI and canopy closure is rather low.

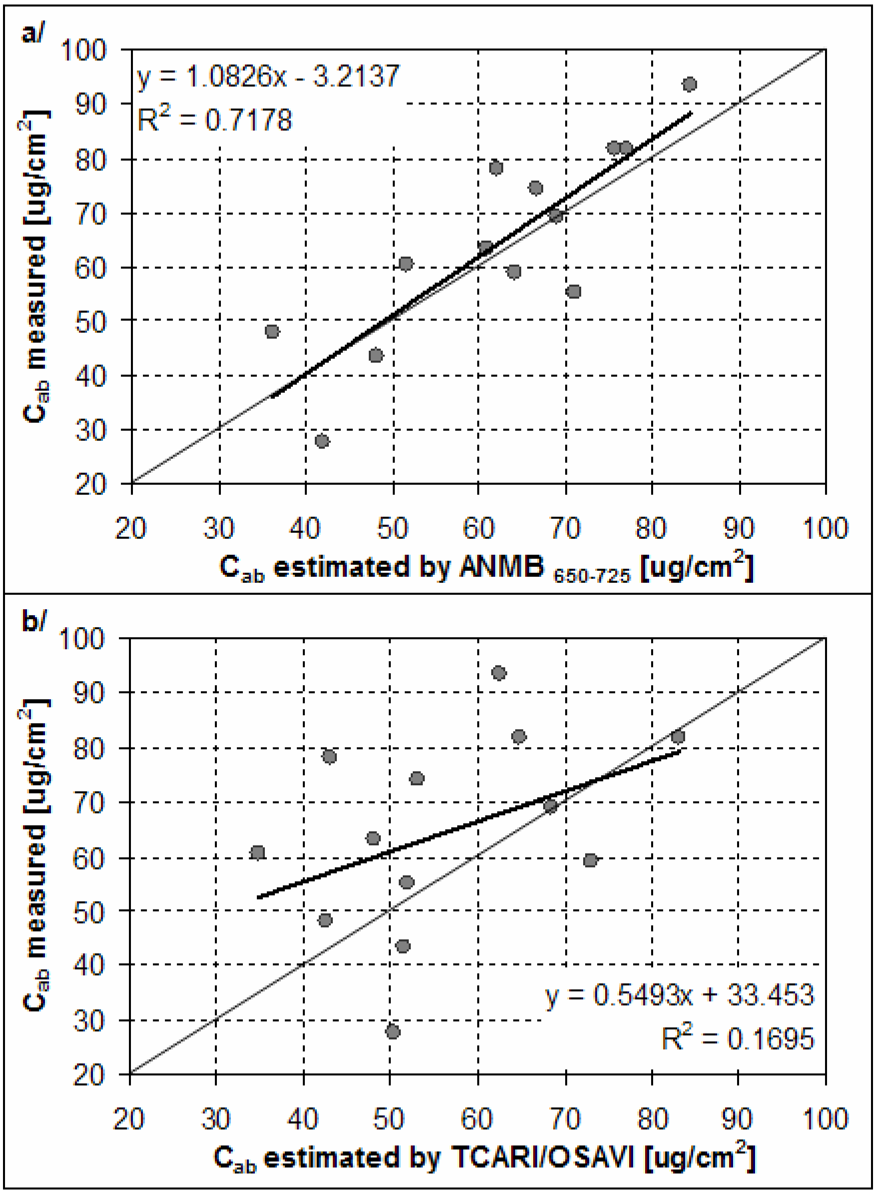

Figure 3. One-to-one relationship and linear regression of chlorophyll concentration measured for 13 sample spruce crowns and estimated by the optical index: a/ $ANMB_{650-725}$; b/ TCARI/OSAVI.

The linear regression of the C_{ab} amount and $ANMB_{650-725}$ (y = 8.7182x - 362.43) obtained from the HDRF database was highly significant (r^2 = 0.9798) and comparable with the logarithmic regression (y = -49.056Ln(x) - 25.738) between C_{ab} concentration and the ratio TCARI/OSAVI (r^2 = 0.9731). However, the final C_{ab} concentration for 13 sample trees estimated by means of both optical indices differs in accuracy. Plots of figure 3 and RMSE values computed between assessed and measured C_{ab} concentrations show considerably higher prediction accuracy for the $ANMB_{650-725}$ (RMSE = 9.53 μg/cm^2) than for the TCARI/OSAVI index (RMSE = 18.83 μg/cm^2). Subsequently, the coefficient of determination for a linear regression established between measured C_{ab} and estimated C_{ab} is high for $ANMB_{650-725}$ (r^2 = 0.7178) and quite low for TCARI/OSAVI (r^2 = 0.1695). These results suggest an appropriate and generally acceptable accuracy of the $ANMB_{650-725}$ chlorophyll content prediction from sunlit forest canopy pixels of very high spatial resolution.

Introduction of 20% of an epiphytic lichen spectral signature into the canopy optical properties of the sample spruce trees did not result in a significant decrease of the $ANMB_{650-725}$ estimation preciseness (RMSE = 10.51 $\mu g/cm^2$; r^2 = 0.6689). As expected, simulated combined influence of the lichen occurrence within the crowns with computer-generated high sensor noise (SNR = 5) caused a decline in the $ANMB_{650-725}$ prediction accuracy (RMSE = 12.13 $\mu g/cm^2$; r^2 = 0.5325), but the accuracy was still higher than for the TCARI/OSAVI estimation without any disturbing effects. However, it has to be stressed that the $ANMB_{650-725}$ index is computed as a HDRF shape parameter through the wavelengths of the high C_{ab} absorption feature, which means within a quite low reflectance signal. Any noise weakening the signal and disturbing the shape of the reflectance curve will cause a decrease of the chlorophyll prediction ability.

CONCLUSIONS

A new optical index $ANMB_{650-725}$ for estimation of the canopy chlorophyll concentration from hyperspectral remote sensing data of a very high spatial resolution was proposed and causally explained. The $ANMB_{650-725}$ is based on qualitative (shape) information of the vegetation reflectance curve rather than on the quantitative reflectance changes driven by the total chlorophyll content. First tests and a sensitivity analysis of the $ANMB_{650-725}$ proved its robustness and acceptable prediction accuracy for heterogeneous spruce crowns. Even introduction of two disturbing effects, occurrence of spruce epiphytic lichen and simulation of a poor SNR, did not reduce radically the $ANMB_{650-725}$ estimation capability. Nevertheless, new sensitivity analyses are strongly recommended to evaluate further the $ANMB_{650-725}$ index performance.

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