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Retrieval of spruce leaf chlorophyll content from airborne image data using continuum removal and radiative transfer

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We investigate combined continuum removal and radiative transfer (RT) modeling to retrieve leaf chlorophyll a & b content (C_{ab}) from the AISA Eagle airborne imaging spectrometer data of sub-meter (0.4 m) spatial resolution. Based on coupled PROSPECT-DART RT simulations of a Norway spruce (*Picea abies* (L.) Karst.) stand, we propose a new C_{ab} sensitive index located between 650 and 720 nm and termed $ANCB_{650–720}$. The performance of $ANCB_{650–720}$ was validated against ground-measured C_{ab} of ten spruce crowns and compared with C_{ab} estimated by a conventional artificial neural network (ANN) trained with continuum removed RT simulations and also by three previously published chlorophyll optical indices: normalized difference between reflectance at 925 and 710 nm ($ND_{925\&710}$), simple reflectance ratio between 750 and 710 nm ($SR_{750/710}$) and the ratio of TCARI/OSAVI indices. Although all retrieval methods produced visually comparable C_{ab} spatial patterns, the ground validation revealed that the $ANCB_{650–720}$ and ANN retrievals are more accurate than the other three chlorophyll indices ($R^2=0.72$ for both methods). $ANCB_{650–720}$ estimated C_{ab} with an RMSE = 2.27 μg cm^{-2} (relative RRMSE = 4.35%) and ANN with an RMSE = 2.18 μg cm^{-2} (RRMSE = 4.18%), while $SR_{750/710}$ with an RMSE = 4.16 μg cm^{-2} (RRMSE = 7.97%), $ND_{925\&710}$ with an RMSE = 9.07 μg cm^{-2} (RRMSE = 17.38%) and TCARI/OSAVI with an RMSE = 12.30 μg cm^{-2} (RRMSE = 23.56%). Also the systematic $RMSE_S$ was lower than the unsystematic one only for the $ANCB_{650–720}$ and ANN retrievals. Our results indicate that the newly proposed index can provide the same accuracy as ANN except for C_{ab} values below 30 μg cm^{-2}, which are slightly overestimated (RMSE = 2.42 μg cm^{-2}). The computationally efficient $ANCB_{650–720}$ retrieval provides accurate high spatial resolution airborne C_{ab} maps, considerable as a suitable reference data for validating satellite-based C_{ab} products.

1. Introduction

Chlorophyll macromolecules are evolutionarily one of the most stable structures used by photosynthetically active organisms for light harvesting and energy transduction (Ustin et al., 2009). Therefore, they are playing an important role in the assimilation of carbon by green vegetation, accounting for 57 Gt of carbon per year (Normile, 2009). The total amount of chlorophyll pigments, which is reacting on surrounding environmental conditions and stress agents including anthropogenic pollutants (Buonasera et al., 2011), indicate the actual physiological status of plants (i.e. their current health and/or phenological states).

Chlorophyll molecules (mainly *a*, *b*, but also *c*, *d*, and *f*) demonstrate a strong spectral absorption in the blue and red part of the electromagnetic spectrum (Chen et al., 2010). These absorption features allow space-borne mapping of vegetation chlorophyll *a* & *b* content (C_{ab}) from high spectral resolution data acquired by spectrometers (Harris & Dash, 2010). A challenging task is, however, to validate the accuracy of satellite maps that are derived at broad spatial resolutions ranging from tens to hundreds of meters (Dash et al., 2010; Stagakis et al., 2010). Although C_{ab} is relatively stable during the high vegetation season, it changes rapidly at the beginning and at the end of the season. Therefore, traditional ground based validation of satellite maps is not only time consuming and expensive, but also potentially inaccurate due to the need of collecting many chlorophyll samples in a relatively short time. An alternative solution for spatial

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validation of satellite products might be the use of high spatial resolution chlorophyll maps retrieved from airborne imaging spectrometers (Moorthy et al., 2008; Zarco-Tejada et al., 2004; Zhang et al., 2008).

High spatial resolution mapping of forest C_{ab} needs to account for the spatially heterogeneous structure of the forest environment (Verrelst et al., 2010). The hierarchical canopy architecture, resulting from foliage clumping at several spatial scales (Písek et al., 2011; Smolander & Stenberg, 2003; Stenberg, 1996), and the presence of various non-photosynthetic scatterers (e.g. branches and trunks) induces strong reflectance anisotropy and high spatial variability (Malenovský et al., 2008). The confounding influence of forest structure on imaging spectrometer-based retrievals of foliar biochemistry can be minimized by combining a continuum removal method (Clark & Roush, 1984) with vegetation canopy radiative transfer (RT) modeling (Myneni, 1991).

The reflectance continuum removal transformation enhances and standardizes specific absorption features of the foliar biochemical constituents (Broge & Leblanc, 2001), in our case chlorophylls. Kokaly and Clark (1999) used normalized band depths calculated from specific continuum-removed (CR) absorption features of leaf reflectance to estimate concentrations of nitrogen, lignin, and cellulose. Curran et al. (2001) refined this methodology and employed CR band depths normalized to i) the band depth at the center of the absorption feature (abbreviated BNC) or ii) the area of the absorption feature (abbreviated BNA) to estimate C_{ab}. Underwood et al. (2003) used the CR technique for mapping invasive plant species, Kokaly et al. (2003) for discriminating different vegetation types in the Yellowstone National Park, and Schmidt and Skidmore (2003) for differentiating saltmarsh vegetation types. More recently, the CR based methods have been successfully applied to map subgenera of two Australian Eucalyptuses (Youngentob et al., 2011), or to quantify grass forage nutrients of an African savanna (Knox et al., 2011).

Three-dimensional (3D) RT models simulate photon interactions with objects within the solar reflective and/or emissive part of the electromagnetic spectrum (Kimes & Kirchner, 1982; Myneni et al., 1992). Radiative transfer of complex natural and urban landscapes is modeled using various computing techniques such as ray tracing or discrete ordinate methods (Disney et al., 2000; Gastellu-Etchegorry et al., 2004). Several 3D models were designed with an intention to simulate physically RT within forest environments of high structural complexity (Disney et al., 2006; Schaepman et al., 2009; Widlowski et al., 2006, 2008). This ability makes them ideal to develop methods that can separate and suppress the confounding influence of forest structure on estimates of foliar biochemistry (Zarco-Tejada et al., 2001).

Several previously published studies have introduced a concept of estimating C_{ab} from airborne high spatial resolution imaging spectroscopy data with optical indices upscaled from leaf to canopy level using vegetation radiative transfer modeling (Haboudane et al., 2002; le Maire et al., 2008; Moorthy et al., 2008; Zhang et al., 2008). Following this concept, the objective of our study is to investigate the potential use of continuum removal transformation for quantitative C_{ab} mapping from airborne data of sub-meter spatial resolution. For this purpose, we use reflectance spectra of Norway spruce (*Picea abies* (L.) Karst.) crowns simulated using a coupled PROSPECT-DART leaf-canopy RT model and we propose a new continuum removal based optical index termed $ANCB_{650–720}$.

2. Materials and methods

As this study exploits several interconnected remote sensing/ground observations, laboratory analyses, and computationally intensive methods, we first describe a general synopsis of principal methodological steps shown in Fig. 1. Field measurements collected during a ground/flight campaign were used: i) to process spectral images acquired with an airborne imaging spectrometer, ii) to parameterize PROSPECT-DART radiative transfer modeling, and also iii) to produce the validation dataset (ground truth) for ten sampled spruce trees. The spectral bands simulated by the DART model allowed us to establish a statistical relationship between C_{ab} and four C_{ab} sensitive optical indices, i.e. a new optical index named Area under continuum-removed curve Normalized to the Chlorophyll absorption Band depth between 650 and 720 nm ($ANCB_{650–720}$) and three published indices: Normalized Difference between reflectance at 925 and 710 nm ($ND_{925\&710}$; le Maire et al., 2008), Simple reflectance Ratio between 750 and 710 nm ($SR_{750/710}$; Zarco-Tejada et al., 2004) and TCARI/OSAVI ratio (Haboudane et al., 2002). The RT simulations were also used to train a C_{ab} estimating artificial neural network (ANN; Bacour et al., 2006; Combal et al., 2003). C_{ab} of sunlit parts of Norway spruce crowns were estimated from geocoded, radiometrically and atmospherically corrected airborne spectral images of an AISA Eagle spectrometer by applying the following methods: i) the statistical relationships established between C_{ab} and the optical indices and ii) the properly trained ANN. The ANN results are cross-compared with estimates of the optical indices, including the newly proposed $ANCB_{650–720}$ index. Finally, the accuracy of the C_{ab} retrievals is validated with ground (laboratory) measured C_{ab}, extracted from needle samples of ten spruce tree crowns. The following subsections are further detailing each methodological step illustrated in Fig. 1.

2.1. Experimental test site

A Norway spruce monoculture located nearby the permanent experimental eco-physiological research station Bílý Kříž in the Moravian-Silesian Beskydy Mountains (eastern part of the Czech Republic; 18.54°E, 49.50°N, altitude 936 m above sea level) was chosen as test site of this study. In 2004 the regularly spaced 26 years old spruce stand had a canopy height between 10 and 12 m, an average diameter at breast height (DBH) of about 13 cm and a leaf area index (LAI) ranging between 7 and 9 m^2 m^{-2}. The Norway spruce

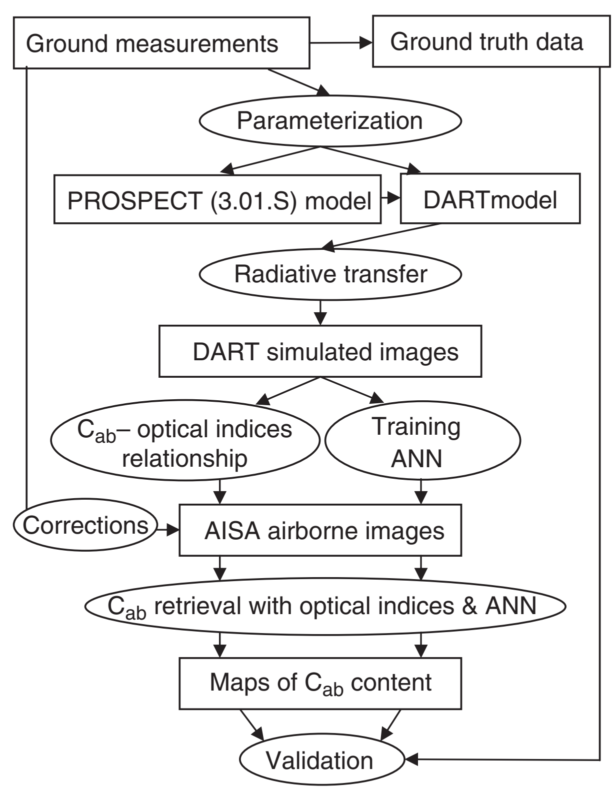

Fig. 1. Basic methodological steps of the study. Rectangular objects represent the input/output data or models, while ellipsoidal objects represent the data processing and other operations (C_{ab}~leaf chlorophyll *a* & *b* content, ANN~Artificial Neural Network, AISA~Airborne Imaging Spectroradiometer).