MEASURING WATER AND CHLOROPHYLL CONTENT ON THE LEAF AND CANOPY SCALE

Henning Buddenbaum[1]*, Pyare Pueschel*[1]*, Marion Stellmes*[1]*, Willy Werner*[2]*, and Joachim Hill*[1]

1. University of Trier, Remote Sensing Department, Trier, Germany; {buddenbaum / p.pueschel / stellmes}(at)uni-trier.de
2. University of Trier, Geobotany Department; werner(at)uni-trier.de

ABSTRACT

Interpreting hyperspectral images of forests can be challenging because reference measurements are difficult to obtain. Forest stands are too high for field spectroscopy, and up-scaling leaf reflectance to canopy reflectance is not straightforward. We took reflectance, transmittance and water and chlorophyll content measurements of forest leaves collected by tree climbers. On the leaf level good agreement between the measured chemical properties and reflectance model inversion results was achieved. The measured spectra were up-scaled into canopy spectra using a GORT model. The up-scaled spectra agreed well with a HyMap image showing pronounced BRDF effects but worse with a "corrected" HyMap image pretending nadir viewing.

INTRODUCTION

Hyperspectral, also known as Imaging Spectroscopy, data have been used for deriving biochemical variables like water and chlorophyll content in forests for some time (1), but current methods have not delivered unambiguous results and operational methods (2). With even more imaging spectroscopy data becoming available in the near future through the spread of affordable airborne sensors like the AISA series by SpecIm or the HySpex series by NEO and the upcoming launch of the satellite EnMAP (3,4), reliable, robust and operational methods become more and more necessary. While deducing water and chlorophyll content from leaf spectra is relatively straightforward (5), deriving chemical leaf properties from remotely sensed canopy spectra is still challenging, mainly because of the heterogeneous structure of the crown layer with several levels of clumping and mutual shading. Although statistical methods based on spectral transformation sometimes show good results (6), model-based approaches are more promising for regularly deriving leaf water and chlorophyll content because they can explicitly account for illumination and observation geometries and variable forest structures.

This paper deals with the analysis of leaf samples collected during an extensive field campaign associated to an imaging spectroscopy overflight, and with the up-scaling of the results from leaf level to canopy level using a geometric-optical radiative transfer (GORT) model.

The field campaign took place in the Pfälzerwald forest near Kaiserslautern, Germany, at a core site of the forest research group within the EnMAP Core Science Team. The site was set up and is maintained by the local forest administration, the geobotany department at Trier University and by the Interreg IVb project ForeStClim (http://www.forestclim.eu). It is equipped with instruments measuring variables like the sapflow, stem growth, soil moisture and climatic parameters and will be used within repetitive airborne hyperspectral imaging campaigns in the future.

MATERIAL AND METHODS

Field and laboratory measurements

In order to relate the reflective properties on the leaf and canopy scale to biophysical parameters professional tree climbers were hired to collect branch and leaf samples from within the sunlit upper part of the crowns from five to ten trees in four different deciduous stands (young and old beeches and oaks, respectively). Two branches were taken from each tree and five leaves of each branch were measured according to the following protocol, the remaining leaves were collected for chemical laboratory analysis. In total, 236 leaves were measured. We measured reflectance and transmittance in the 350–2500 nm spectral range using a FieldSpec2 with a Contact Probe and a Leaf Clip (ASD Inc., Boulder, CO, USA). The Contact Probe is a spectrometer attachment with a light source covering a 10 mm radius; the Leaf Clip is a fixture to clamp leaves between the light source/sensor head and an interchangeable black or white background. By measuring radiance reflected by the leaf with dark and bright background, reflectance and transmittance can be calculated. The Leaf Clip/Contact Probe assembly guarantees constant illumination and viewing geometry and shields the sample from ambient light (7). In addition, fresh leaf weight, chlorophyll content using a Minolta SPAD 502 chlorophyll analyzer and the leaf area using a scanner in the field were measured. The leaves were then taken to the laboratory, oven-dried and weighed again to deduce the equivalent water thickness (EWT) gravimetrically.

Image data

At the first day of the field campaign in August 2009 two HyMap hyperspectral images of the area were acquired. The images have a ground sampling distance of 5 and 10 m, respectively. The sensor records images in the spectral range of 450 to 2480 nm in 125 bands with 13 to 21 nm bandwidth. 512 lines are recorded with 60° FOV and about 2.5 mrad IFOV (8). The images were radiometrically and atmospherically corrected and geocoded.

The higher resolution image was recorded under particular illumination and observation conditions with the sensor looking directly into the principal plane. Two versions of this image are available: One version contains the reflectances as measured and displays a strong brightness gradient from NW to SE. The other version has been objected to a cross-track illumination correction resulting in uniform brightness (9).

Reflectance modelling

On the leaf level we used the reflectance model PROSPECT-3 (10,11). In forward mode a Matlab implementation was used, the inversion was done using a Powell minimisation routine in Delphi. Use of PROSPECT-4 (12) was also considered, but PROSPECT-3 spectra matched the measured leaf spectra better (Figure 1).

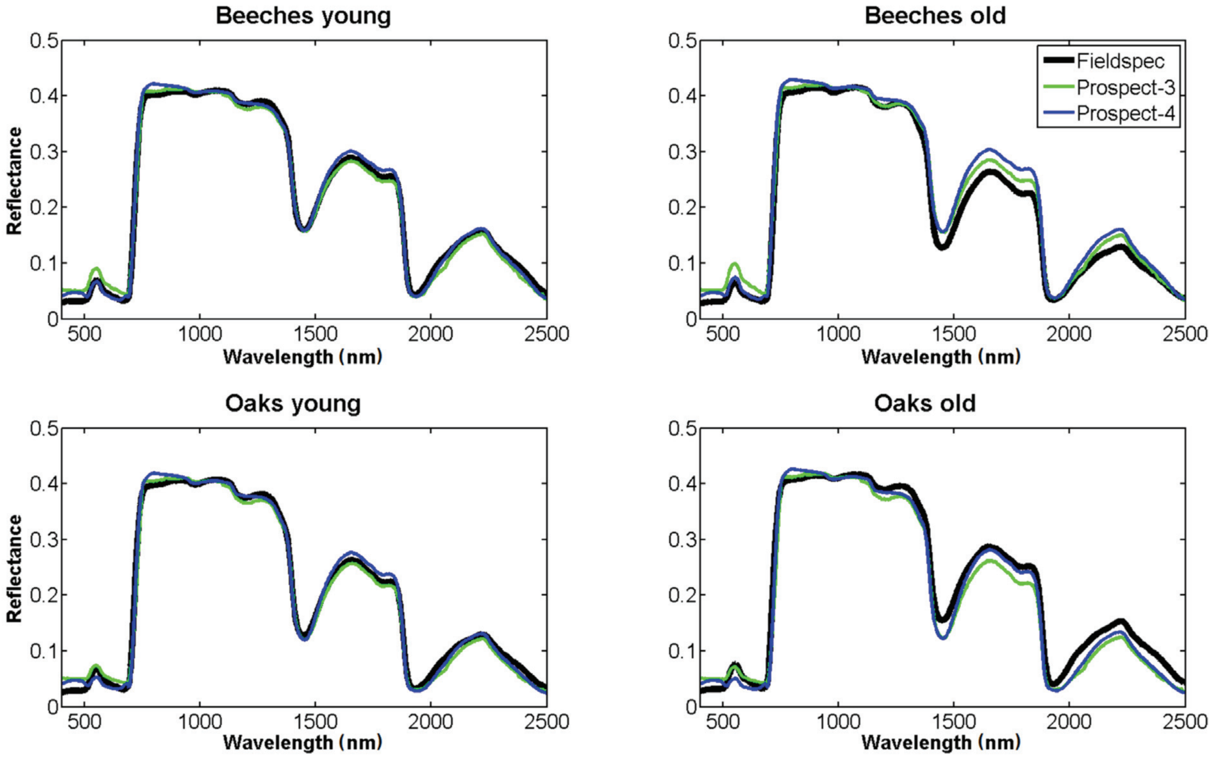

Figure 1: Mean leaf reflectance spectra and forward modelling results of Prospect-3 and -4.

In order to model canopy spectra for the stands considered an adapted version of the model INFORM (13) was used. INFORM originally is a combination of the leaf reflectance models PROSPECT or LIBERTY, the homogeneous canopy model SAILH (14) and the forest reflectance model FLIM (15). Our adaptation consists of a replacement of the leaf reflectance model with actual leaf spectra. Based on structural parameters of the respective stands measured in the field and measured soil spectra, the mean leaf reflectance and transmittance spectra of each stand were scaled up to canopy level using the adapted version of INFORM. This was done for both versions of the HyMap image. In the first up-scaling model run, the actual illumination and viewing geometry was modelled, in the second model run all stands were modelled for nadir viewing conditions.

RESULTS

Leaf level

Plotting gravimetric EWT in measuring order revealed a clear dependence on time of day for the three measuring days (Figure 2a). A plot against measuring time of day showed a linear relationship for our samples (Figure 2b). Using this relation we were able to normalize EWT to the HyMap overflight time. For considerations on the leaf level no normalization was applied. Three outliers with negative or extreme measured EWT were excluded from further analysis (marked with red circles).

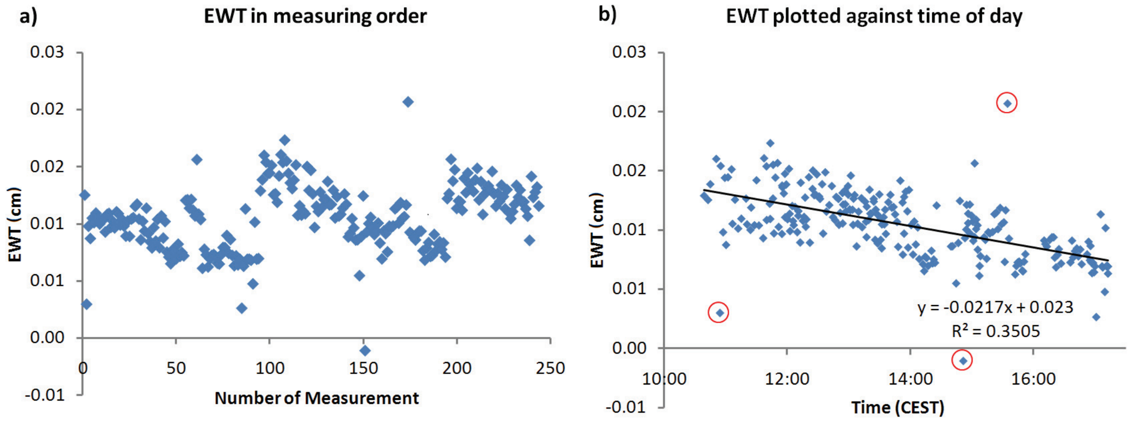

Figure 2: Gravimetric EWT depending on measuring time.

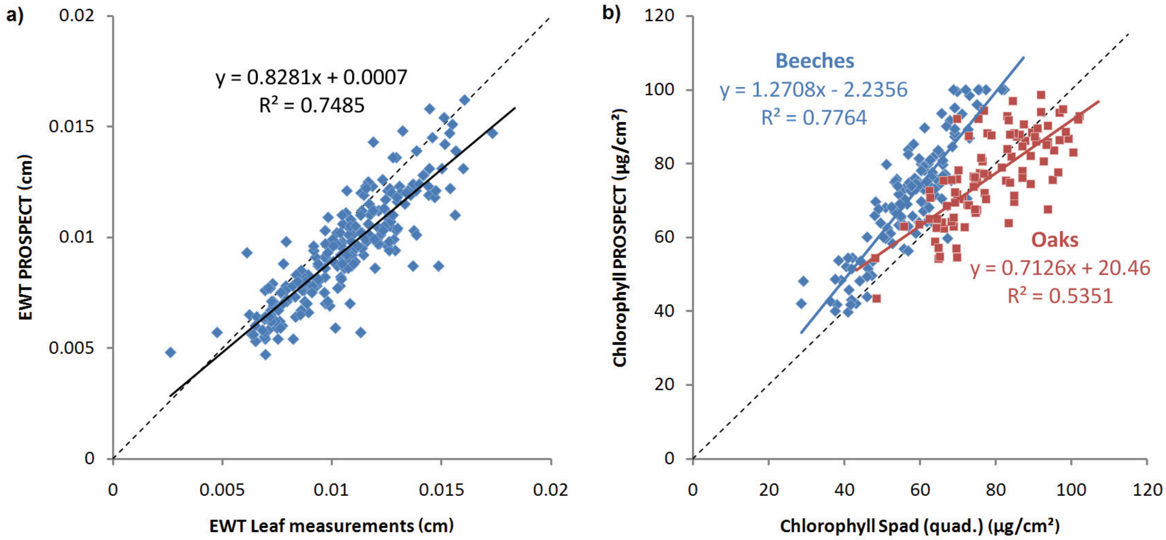

Figure 3: Equivalent Water Thickness measured gravimetrically and Chlorophyll measured by SPAD against PROSPECT model inversion values, with 1:1 lines.

An inversion of the PROSPECT-3 leaf reflectance model showed good agreement with measured EWT and chlorophyll content (Figure 3). SPAD values (M) were transferred to Chlorophyll concentrations using the equation $Chl = 10^{\left(M^{0.285}\right)}$ where Chl is given in µmol/m^2 (16), which in earlier studies rendered the relationship between SPAD meter values and chlorophyll measured in chemical extraction well. In this study, the relation between SPAD and PROSPECT chlorophyll is not unbiased. The relationship between chlorophyll values derived from SPAD measurements and Prospect inversion results is different for beech and oak leaves.

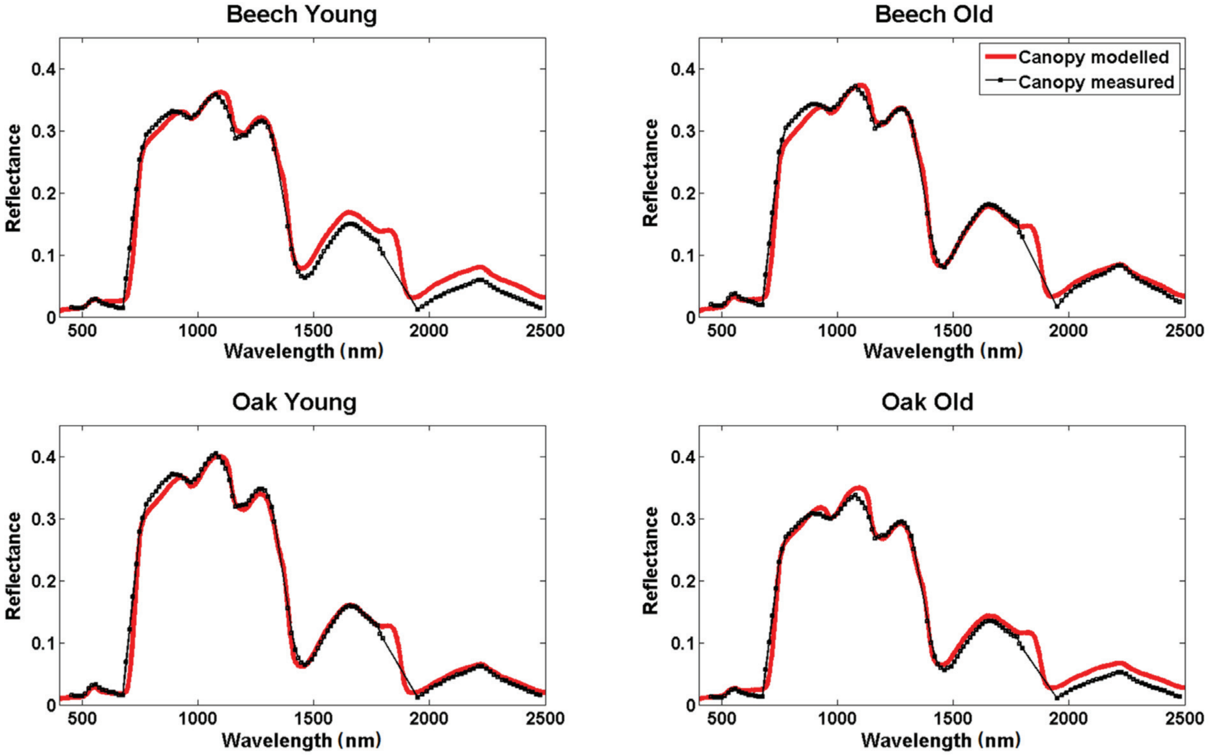

Figure 4: Measured leaf reflectance spectra, modelled canopy spectra and HyMap canopy spectra.

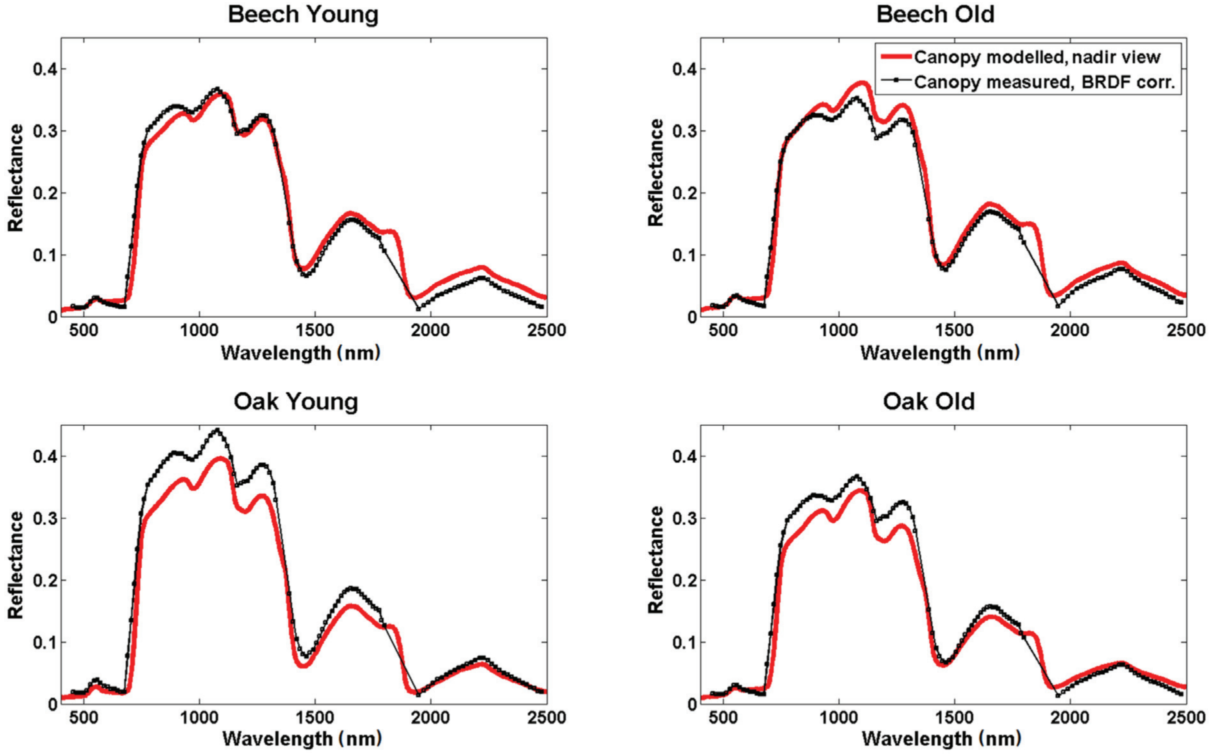

Figure 5: Modelled canopy spectra under nadir viewing conditions and HyMap spectra with across-track illumination correction.

Canopy level

Resulting canopy model spectra from the INFORM run using the actual illumination and viewing geometry exhibit an excellent agreement with HyMap image spectra without cross-track illumination correction of these stands (Figure 4). Model spectra with the correct illumination but nadir viewing geometry and the respective spectra in the illumination corrected image are depicted in Figure 5. In this case the agreement between modelled and observed spectra is distinctly worse. None of the stands lies in the regions strongly influenced by the bidirectional reflectance distribution (BRD) effects, but still the differences are clearly visible. The young beech and oak stands and the old oak stand lie SE of the nadir line, the old beech stand lies to the NW.

DISCUSSION

Forest leaf reflectance measurements are a challenge, especially due to the limited crown accessibility. In addition the crowns are heterogeneous and contain sunlit and shadowed leaves with different properties and many leaves are perforated. So it is very difficult to collect exhaustive leaf samples. As a consequence the limited number of leaf samples should be used for validating results from the inversion of reflectance models rather than for trying to establish stable and transferable statistical relationships.

The combination of FieldSpec, Contact Probe and Leaf Clip seems to be an appropriate instrumentation for leaf reflectance and transmittance measurements in the field. One should pay attention to the minimum leaf size required for the measurement and that there should be no holes in the leaves, especially for transmission measurements.

The results of the leaf reflectance model inversion were satisfactory, although chlorophyll estimation accuracy varied for beeches and oaks. The relationships between measured water content and model inversion results were the same for both tree species.

The model results on stand level clearly show that cross-track illumination correction can be dangerous. Correcting BRD effects is advantageous for statistical analyses like classification or regression (9,17). These analyses require objects of the same quality or quantity to have nearly the same spectra all over the image. But the statistics-based correction of the non-uniform brightness does not take into account that a sensor detects different objects on the land surface when looking at forests under slanted or nadir viewing angles: the relative leaf angles and the amount of soil, undergrowth, bark and shadow visible are different. These effects cannot be corrected with a statistical cross-track illumination correction, but they can be accounted for by geometric-optic radiative transfer models. These findings underline that although INFORM is a very simple canopy reflectance model, it is able to reproduce forest stand spectral responses under illumination and observation geometries which come close to hot-spot conditions (18) and that a statistical illumination correction is not sufficient for all types of analyses (19).

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