RETRIEVAL OF LAI FROM AIRBORNE HYPERSPECTRAL AND AIRBORNE LASER SCANNER DATA USING A CANOPY REFLECTANCE MODEL

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ABSTRACT

Against the background of regional climate change impacts the development of adapted forest management strategies asks for reliable biochemical and structural forest information provided by remote sensing systems. Hyperspectral imaging has the potential to contribute such information. However, given the dynamic behavior of forest ecosystems it is advisable to replace empirically based retrieval strategies through conceptually-based interpretation frameworks. This paper explores the use of structural stand parameters derived from full-wave LiDAR (light detecting and ranging) systems for regularizing the inversion of a geometrical optics forest reflectance model (INFORM) with bi-directional capacity. The results suggest that LiDAR systems provide suitable stand parameters which, in addition to be used in restricting the inversion of reflectance models, can efficiently increase the quality and spatial coverage of reference data for optimizing these models.

1. INTRODUCTION

As in many regions of Central Europe forest systems in the Federal State of the Rhineland Palatinate in Germany are expected to become impacted by effects of regional climate change. Given the large economic and environmental value of forest in this region (about 40 % of the state surface) the design of adapted forest management strategies is currently pursued in the context of the EU-Interreg-IV Project ForestClim (http://www.forestclim.eu). Reliable and consistent information on state, structure and development of forest ecosystems is an essential requirement in this process. Given the financial and logistic limitations of collecting data through terrestrial surveys it becomes evident that remote sensing has a major role to play.

In a study on evaluating empirical-statistical relationships between airborne hyperspectral data and key forest variables Schlerf et al. [1] had successfully tested correlations between all possible two-band orthogonal narrow-band vegetation indices and field-measured leaf area index (LAI) for spruce stands. The best combination they found was the index related to the wavelengths at 1088 and 1148 nm ($r^2 = 0.77$, rel. RMSE = 17%) which are associated to the needle water content. As successful as the LAI estimates for this particular situation has been, it is clear that the empirical model is not transferable to acquisition dates with different canopy water content. To overcome these limitations alternative methods are needed which are less sensitive to particular eco-physiological conditions. The inversion of adequate canopy reflectance models is considered such an alternative.

Adequate reflectance models need to account for the geometric complexity of forest stands. Among others, the Invertible Forest Reflectance Model INFORM concept [2], a combination of the models LIBERTY [3] or PROSPECT [4, 5] (depending on the type of trees) with SAILH [6, 7] with the geometric-optical concept of FLIM [8], has been found to provide suitable alternative. However, also this approach is sensitive to the well-known ill-posed problem when retrieving stand parameters through different inversion strategies. For increasing model robustness in the inversion mode we intend to use structural information derived from active optical remote sensing systems (LIDAR). The concept is to regularize the inversion of INFORM through parameters which can be derived with sufficient accuracy from airborne LIDAR systems (tree height, crown length/diameter, number of trees per unit area).

2. STUDY AREA

The area of study (49°40'N, 7°10'E) is the Idarwald forest in south-western Germany on the north-western slope of the Hunsrück mountain ridge. The dominant tree species are Norway spruce (*Picea abies*), beech (*Fagus sylvatica*), oak (*Quercus petraea*) and Douglas fir (*Pseudotsuga menziesii*). The Idarwald forest is a managed forest containing deciduous and coniferous stands in many different age classes showing a relatively large range of LAI values. Active forestry practices in this area include selective cutting, plantation establishment and thinning.

3. MATERIAL

We used a hyperspectral image recorded by the HyMap system in 2003. A full waveform, small footprint airborne Laser scanner dataset recorded in 2005 together with field data also collected in 2005.

The HyMap [9] image includes 126 bands in the spectral range between 420 and 2480 nm with a mean spectral resolution of 15 nm. 4 of the channels were deleted because of a bad SNR so that the dataset contains 122 channels. The sensor was flown about

Proc. 'Hyperspectral 2010 Workshop', Frascati, Italy,
17–19 March 2010 (ESA SP-683, May 2010)

2000 m above ground, resulting in a spatial resolution of 5 m. During the HyMap image recording the sun zenith angle was 28.5°, the azimuth angle was 165°. The flight line was oriented SW-NE with an across-track scanning angle of 133°. As the scan lines are oriented only 28° off the principal plane, strong bidirectional illumination effects are present. Some of the stands considered lie a the edge of the image strip with viewing angles of up to +/–30°, so a model that is supposed to correctly represent these spectra needs to model the hot spot effect accurately. Fig. 1 shows the directional dependence of reflectance spectra for the viewing geometry in the HyMap image.

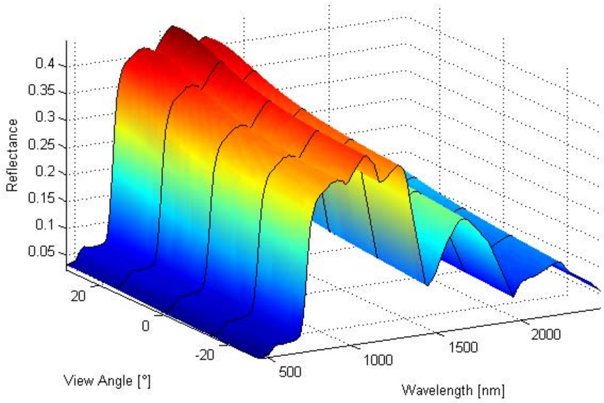

Figure 1. Beech spectra seen with viewing angles between −30° and +30°, 28° off the principal plane, as modeled by Inform.

The laser scanning data set was recorded using a Riegl LiteMapper 5600 [10], a waveform-recording small-footprint discrete-pulse Laser scanner. The average pulse density was 4 points m^{-2}.

In addition to the remote sensing data, field work was conducted in September 2005. 28 stands of Norway spruce and beech were sampled in plots of 30 m × 30 m size. Parameters measured included tree height, crown height, crown radius in four directions, stem diameter at breast height, LAI, number of trees and canopy closure. Nine hemispherical digital photos using a fish-eye lens were taken of each stand in order to document the stand structure.

4. METHODS

Leaf Area Index (LAI) was established in three ways: In the field, remotely sensed using laser scanner data and remotely sensed using hyperspectral data and model inversion.

4.1. LAI Field measurements

In the field, we measured LAI using a Li-Cor LAI 2000 Plant Canopy Analyzer [11]. In each stand we recorded LAI at 10 different locations. The above-canopy measurements were conducted on a large clearance after the below-canopy measurements. The sky was overcast so that the error due to non-synchronous measurements is estimated to be low. The mean LAI value of each stand was taken to be representative. No LAI post-processing was conducted. The range of field-measured values is presented in tab. 1.

Table 1. Range of structural parameters measured in the field

	Min	Max	Mean
Stand Age	10.0	238.0	75.1
Trees/ha	11.0	532.0	97.1
Height	7.0	35.4	22.4
Crown diameter	1.8	13.3	5.9
LAI	2.2	6.0	3.8

4.2. Structural forest parameter estimation using laser scanning

A reference map of LAI was assessed from the laser scanning data via the fractional cover. Hopkinson & Chasmer [12] compared four methods for deriving the fractional cover from laser scanning. All methods are based on comparing the amount of laser energy reaching the ground and the total laser energy reflected. The study found that a method called $FC_{\mathrm{Lidar(BL)}}$ (BL meaning “Beer’s Law”) gave unbiased and robust results. In this approach the fractional cover of a pixel is calculated according to Eq. 1 using the sums of intensities of different kinds of Lidar pulses on the ground or reflected anywhere in the pixel. $I_{GroundSingle}$ are single return pulses reflected on the ground, I_{Single} are all single return pulses. $I_{GroundLast}$ are last return pulses reflected on the ground, I_{Last} are all last return pulses. I_{First} are the first return pulses, I_{Interm} are intermediate return pulses, and I_{Total} are all pulses of all types.

$$FC = 1 - \left(\frac{\dfrac{\Sigma I_{GroundSingle}}{\Sigma I_{Total}} + \sqrt{\dfrac{\Sigma I_{GroundLast}}{\Sigma I_{Total}}}}{\dfrac{\Sigma I_{First} + \Sigma I_{Single}}{\Sigma I_{Total}} + \sqrt{\dfrac{\Sigma I_{Interm} + \Sigma I_{Last}}{\Sigma I_{Total}}}} \right) \quad (1)$$

The values agree well with fractional covers derived from the hemispherical photos taken in the field (R^2 = 0.75).

LAI was derived from fractional cover using Eq. 2, a relationship from [13]:

$$LAI = \frac{-1}{b \cdot G(\theta = 0) \cdot \Omega} \cdot \frac{\ln(a_0 - FC)}{a_0} \quad (2)$$

where b characterizes the spectral dependence of radiation interception, $G(\theta=0)$ is the leaf projection factor, Ω accounts for a degree of dependence on the position of the vegetation stands and a_0 is an empirical coefficient introduced to avoid LAI values larger than 6 in closed stands. Following [7], b is fixed at 0.945, $G(\theta=0)$ is 0.5 and a_0 is set to 1.05 to avoid LAI values larger than 6 for closed stands. In order to get unbiased LAI estimates, the clumping parameter Ω is set to 1 for deciduous stands and 0.6 for coniferous stands.

The relationship between the field measurements and the LAI derived from laser scanning is shown in Fig. 2 (for beech stands) and Fig. 3 (for spruce stands). The dashed line shows the 1:1 relationship, the solid line is a linear regression without intercept.

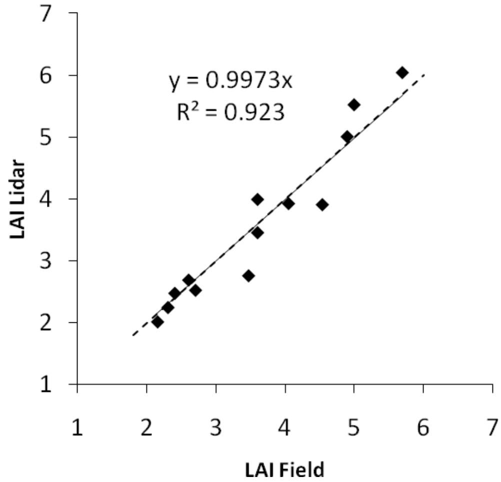

Figure 2. Relationship of field-measured LAI and LAI derived from Lidar for beech stands.

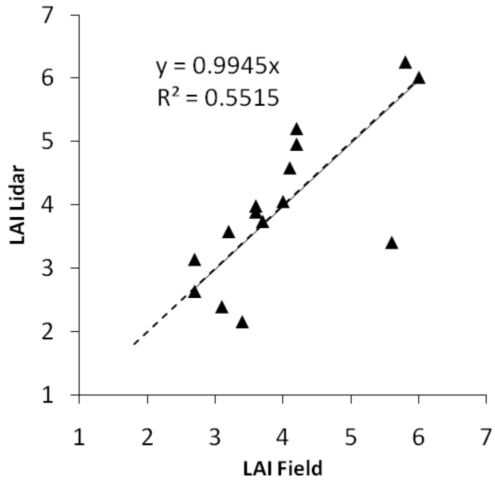

Figure 3. Relationship of field-measured LAI and LAI derived from Lidar for spruce stands.

In addition to LAI, tree heights were derived from the laser scanning data with high accuracy ($R^2 = 0.91$). As full waveform information was available, it was also possible to measure crown lengths and crown base heights with acceptable accuracy ($R^2 = 0.62$). The number of trees per hectare was also derived from the LiDAR data, using a tree tip finding algorithm in a moving window. The window size was chosen depending on tree height and a good correlation with stem number measured in the field was found ($R^2 = 0.76$).

4.3. Reflectance modelling

We conducted a forward modelling of the beech stands using the input parameters measured in the field, illumination and viewing geometry of the stands in the HyMap image and default values for leaf composition (structure index, water and chlorophyll content), ground reflectance and average leaf inclination angle. The model's main structural parameters are number of trees per hectare, crown diameter and tree height.

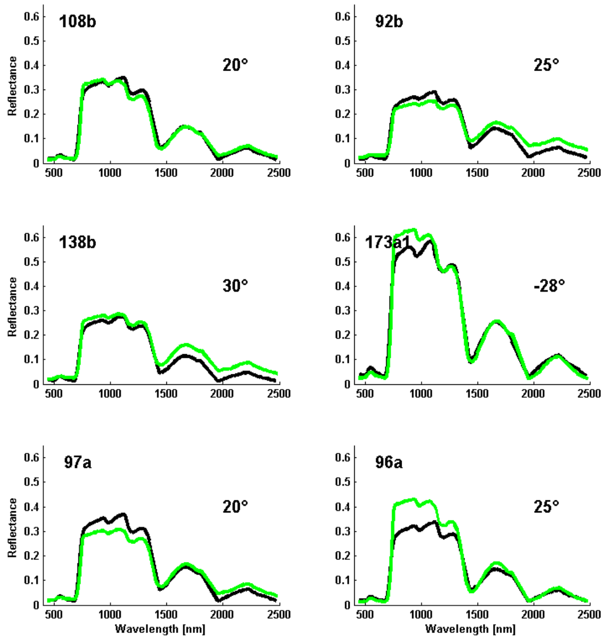

Figure 4. Image spectra (black lines) and model spectra (green lines) for six beech stands.

Fig. 4 shows six examples of stand spectra that were modeled using INFORM together with the corresponding image measurement. The majority of the stand reflectance signatures were modelled with good accuracy compared to their respective HyMap spectra, but some modelled spectra show large deviations from the image spectra.

When compared to the respective HyMap reflectance signatures most of the stand reflectances appear to be modeled with good accuracy. However, some model results exhibit significant differences to the measured reflectance, without that obvious reason for a failure of the model can be identified. To the contrary, field-measured stand parameters for stand 96a (689 trees/ha, 3.7 m average crown diameter, stand LAI 3.6), for example, suggest a substantially larger leaf biomass (LAI) on stand level than those of stand 97a (577 trees/ha, 3 m average crown diameter, stand LAI 2.3).

This is accounted for by the modeled reflectance for stand 96a (which exhibits more intense backscattering effects in the NIR plateau, as well as higher absorption effects in the VIS and SWIR spectral range) while the HyMap measurements for both stands exhibit contradictory stand spectra. Such findings to some extent also emphasize the complexity of collecting representative data on stand structures within forest environments, owing to reduced GPS-positioning accuracy, large within-stand variability, error budget of applied field methods and others.

We conclude that the available reference measurements show some inconsistencies which need further analysis before designing the inversion process. However, as strong correlations between the terrestrial measurements and the LiDAR-derived stand values of LAI, crown dimensions, and tree densities suggest, it appears feasible to use the LiDAR measurements for substantially increasing the set of terrestrially observed reference stands.

5. RESULTS AND DISCUSSION

When combining the LiDAR-derived stand information with the existing digital spatial forestry data base (WÖFIS), an increased spatially distributed sample of LiDAR-derived reference stands can be produced. Together with the associated stand data (dominant tree layer, age and development phase, wood volume, etc.) this enhanced reference data base can be separated in two groups, one for validation and another for regularizing the inversion process. This is expected to substantially improve the conditions for evaluating in particular the directional capacities of the INFORM reflectance model. This is of special importance since the available HyMap data set has been acquired under conditions which are close to the hot spot constellation within the principal plane.

Airborne laser scanning has been confirmed as an efficient approach for deriving structural forest parameters which, among other applications, can be used to limit the parameter space for inverting geometric-optical radiative transfer models (GORT). This may assist in efficiently mitigate the ill-posed nature of the inversion problem. In inversion strategies based on look-up tables (LUT), for example, the LiDAR-derived structural parameters can either be used to select only the appropriate LUT entries or to calculate a cost function with penalties assigned to the differences between LiDAR-derived parameters and the LUT [14].

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