

Assessment of Vegetation Nitrogen Status from Hyperspectral Laboratory and Image Data

Martin Schlerf^{1,*}, Joachim Hill¹, Henning Buddenbaum¹, Willy Werner²,
Gebhard Schüler³

¹ Remote Sensing Department, University of Trier, Germany

² Department of Geobotany, University of Trier, Germany

³ Forest Research Institute Rheinland-Pfalz, Germany

Abstract: The research evaluated the information content of HyMap data for the estimation of chlorophyll (C_{AB}) nitrogen (C_N) and water (C_W) concentration in Norway spruce (*Picea abies* L. Karst.) needles. The aims were to find predictive models to estimate chemical concentrations and to systematically compare different types of derivatives of spectral reflectance regarding the accuracy of prediction. The results of the analysis showed that C_{AB} can be well estimated from laboratory and canopy reflectance data. The best predictive model to estimate C_{AB} at the laboratory level yielded a cross-validated R^2 of 0.81 and a relative rmse of 8.7 % ($n=78$). The best model to estimate C_{AB} at the canopy level was achieved using band depth normalised spectra with a cross-validated R^2 of 0.90 and a relative rmse of 2.8 % though the small sample size ($n=13$) is critical. We observed weaker relations between reflectance and the concentration of nitrogen (canopy level: $R^2 = 0.57$, rel. rmse = 4.6 %). For water, poor results were obtained on the canopy level. The wavebands selected in the regression models to estimate C_{AB} were typically located in the red edge region and along the edge of the chlorophyll absorption feature. This result coincides with a general understanding that the maximum correlations occur on the edge of absorption features as the central wavelengths become saturated. For C_N , additional wavebands related to known protein absorption features at 1730 nm, 2180 nm, and 2350 nm were selected. The portion of selected wavebands attributable to known absorption features strongly depends on the type of derivative spectra used. A method called “derivative of water removed spectra” (DWRS) produces the largest percentage of wavebands directly or indirectly related to known absorption features. Larger values of chlorophyll occurred over soils with large base saturation (formed of basalt and colluvium) whereas poorly base saturated soils over sandstone showed lower C_{AB} values. However, in order to assess the spatial variation of photosynthesis, a larger variation of nitrogen has to be considered by extending the study to other ecosystems, such as deciduous forest, vine yards, orchards or grassland.

1. Introduction

Many of the biogeochemical processes in terrestrial ecosystems are related to the content of foliar nitrogen in leaves (Vitousek, 1982; Waring & Running, 1998). Recently, foliar nitrogen or chlorophyll has been increasingly assessed from hyperspectral remote sensing data (Serrano et al., 2002; Mutanga & Skidmore 2004; Zarco-Tejada et al. 2004).

In previous studies, different types of derivatives of spectral reflectance have been used in combination with stepwise multiple regression (SMR, Curran, 1989) to estimate foliar

chemical concentrations, such as first-derivative of reflectance (Demetriades-Shah et al., 1990), continuum-removed (CR) spectra and band-depth normalised (BDN) spectra (Kokaly & Clark, 1999) among others. These derivatives aim to enhance the absorption feature present in vegetation spectra in the first step and SMR in the second step tries to find wavebands located in these absorption features that are related to the investigated chemicals. CR and BDN spectra were most often applied to reflectance spectra of dry leaf samples (Curran et al., 2001) or to absorption features that are not masked by water, for instance the chlorophyll features. Estimation of nitrogen from fresh leaf reflectances in mid-IR wavebands suffers from the disturbing effect of leaf water. To overcome problems associated with leaf water this research combines the strategy of least-squares spectral matching (LSM, Gao & Goetz, 1994; 1995) that attempts to remove the influence of leaf water from a fresh vegetation reflectance spectrum with SMR.

The overall aim of the work was to evaluate the information content of hyperspectral remote sensing data for the estimation of leaf chemical concentrations in forests. More specific objectives were to

- find predictive models by stepwise multiple linear regression technique using characteristic absorption features to estimate concentrations of total chlorophyll (C_{AB}), nitrogen (C_N), and water (C_W)
- systematically compare different types of derivatives of spectral reflectance regarding the accuracy of the predictive models and
- examine the effects of sensor bandwidth and sensor noise on the estimations of chemical concentrations from laboratory reflectance data to assess the transferability of the techniques to remote sensing data

Derivatives of spectral reflectance that were used in combination with SMR to estimate foliar chemical concentrations: Spectral reflectance (RFL), First-difference of spectral reflectance (DRFL), Continuum-removed (CR) spectra, Band-depth normalised (BDN) spectra and First-difference of water removed spectra (DWRS).

2. Method

At Gerolstein test site (Eifel, Germany) 13 stands of Norway spruce were identified that cover the whole range of nutrient availability in the soil (poor sandstone to rich

limestone) in order to achieve a maximum variability in leaf biochemical content. Foliar samples were obtained according to standardised procedures from the upper part of the crown of 3 randomly selected trees within each stand. Foliage from the sampled branches were removed separately by age class and randomly selected subsamples were subjected to routine biochemical analysis for chlorophyll a and b (Lichtenthaler, 1987), water, and nitrogen (Wilson, 1990) concentration. In total, 39 first-year needle samples and the same number of third-year needle samples were obtained. 3rd year samples from poor sandstone sites showed significantly lower values of chlorophyll and nitrogen concentration than the other medium or rich sites.

Needle reflectance (stacked layer) was measured using a high spectral resolution spectroradiometer (Field-Spec-II). Three sets of reflectance were used for further analysis: a) 1 nm spectral resolution, b) degraded to HyMap spectral bands, and c) HyMap spectral bands with a normally distributed noise component added (standard deviation: 0.002). Following approaches by Kokaly & Clark (1999) and Curran et al. (2001), we included the chlorophyll absorption feature at 670 nm and the water absorption feature at 1200 nm, and three absorption features related to protein at 1800 nm, 2100 nm, and 2300 nm into the regression analysis in order to estimate biochemical concentrations. Calculation of the derivatives involved either computation of the derivative followed by an extraction of the features (RFL, DRFL) or extraction of the features followed by the computation of the derivative (CR, BDN). Computation of DWRS is described below. The five features of a single type of derivative were then re-combined into one single data set, normalised band wise to mean of zero and standard deviation of one, and subjected to regression analysis. SMR was run separately for 1st year, 3rd year, and both 1st and 3rd year needle samples. The idea was that each data set contained all information necessary to estimate all of the three chemical substances and to see if the appropriate wavebands were selected from the available bands. Forward SMR was used to develop relationships between chemical concentration and a measure of reflectance for certain wavebands. Cross-validation was employed to assess the accuracy and validity of the regression models. SMR was run under controlled conditions to avoid overfitting of the models to the calibration data.

HyMap was flown over Gerolstein test site at July 14 2003. Radiometric pre-processing consisted of an across track illumination correction to remove the view angle effect, and a combined sensor calibration and correction of atmospheric effects (Hill & Mehl, 2003). The image data were geometrically corrected to subpixel accuracy using the parametric geocoding software PARGE (Schläpfer et al., 1998). Upscaling from leaf to canopy level was achieved by establishing directly a statistical relationship between ground-measured chemical data and

canopy-measured reflectance. For this purpose, chemical data that had been obtained on leaf level was aggregated to stand level by computing the stand mean of year 1 and year 3 needles.

The approach of least-squares spectral matching (LSM; Gao & Goetz, 1994) was modified to enhance the information about protein (one of the major nitrogen bearing leaf constituents) available in fresh leaf material. The spectral reflectance of water $R_{W\text{mod}}(\lambda)$ was modeled from the spectral absorption coefficients of liquid water $k_W(\lambda)$ as:

$$R_{W\text{mod}}(\lambda) = (A + B\lambda)e^{-C_W k_W(\lambda)} \quad (1)$$

where C_W represent the concentration of water and the term $(A+B\lambda)$ represents the background level of the calculated spectrum. Absorption coefficients of leaf water were obtained from Dawson et al. (1998). A , B , and C_W were iteratively adjusted in such a way that the sum of the squared differences between the measured reflectance $R_{F\text{mes}}(\lambda)$ and the modeled reflectance $R_{F\text{mod}}(\lambda)$ for each given waveband was minimized. The residual spectrum (Residual of Spectral Matching, RSM) was calculated which is defined as the difference between the measured fresh needle spectrum $R_{F\text{mes}}$ and the modelled spectrum $R_{F\text{mod}}$ or $R_{W\text{mod}}$ divided by the measured spectrum $R_{F\text{mes}}$ and the first difference of RSM spectra (DWRS) were subjected to the SMR procedure. It was assumed that the residual in the 2.1-2.3 μm spectral region may contain relevant information about protein.

3. Results

A summary of the results is given in Table 1. The analysis of laboratory spectra revealed that C_{AB} was well estimated and just slightly affected by a decrease of the spectral resolution or adding of noise, C_N was moderately well estimated and just slightly affected by a decrease of the spectral resolution or adding of noise and C_W was well estimated with 1-nm data and resampled-to-HyMap data but strongly affected by noise addition. The results also demonstrated that the models used to estimate nitrogen concentration employed wavebands related to

TABLE I. Determination of chemical forest attributes using laboratory and HyMap data and three types of spectral derivatives; DWRS = First-difference of water removed spectra, RFL = Reflectance spectra, BDN = Band-depth normalised spectra; relative rmse: % of mean; percentage of attributable bands: directly or indirectly related to the variable of interest, directly related: ± 30 nm of the chemical of interest, indirectly related: ± 30 nm of a chemical with which the chemical of interest was correlated, approach adapted from Curran et al. (2001)

Data	Chemical	DWRS			RFL			BDN		
		R ²	rmse	Perc. of attrib. band	R ²	rmse	Perc. of attrib. band	R ²	rmse	Perc. of attrib. band
Laboratory resampled	C_{AB}	0.81	7	33	0.80	9	22	0.76	9	21
	C_W	0.77	5	69	0.75	6	57	0.79	5	11

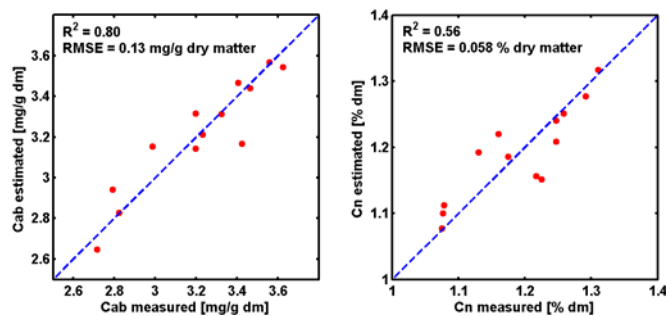


Figure 1. Estimated against measured leaf total chlorophyll concentration (C_{AB}) (left) and estimated against measured leaf nitrogen concentration (C_N) (right).

chlorophyll and protein absorption features. Using DWRS spectra, 73 percent of the selected wavebands by SMR were directly or indirectly related to nitrogen absorption features, whereas with BDN spectra just 50 percent of the wavebands and with RFL none of the wavebands had such a relationship. The wavelengths selected from DWRS spectra are close to protein features at 1730 nm, 2180 nm, and 2350 nm and have been repeatedly selected in previous studies (Johnson et al., 1994; Curran et al., 2001; Serrano et al., 2002). From Field-Spec-II data resampled to HyMap spectral bands plus noise component added, cross-validated rmse for chlorophyll a+b was 0.32 mg g^{-1} dry matter ($r^2=0.75$, 3 wavebands, mean: $3.21 \text{ mg g}^{-1} \text{ dm}$) and for nitrogen 0.083% of dry matter ($r^2=0.47$, 2 wavebands, mean: 1.19% dry matter).

On stand level, chlorophyll concentration (C_{AB}) was well estimated by all methods except reflectance spectra (RFL). The best predictive model to estimate C_{AB} was achieved by band-depth normalisation (BDN) with a cross-validated coefficient of determination (R^2) of 0.90 and a cross-validated relative rmse of 2.8 percent. Continuum-removed spectra (CR) performed less accurate (relative rmse: 4 percent), but used only 2 instead of 3 wavebands in the model. Nitrogen concentration was moderately well estimated by first-difference of water removed spectra (DWRS), CR and first-difference of reflectance spectra (DRFL) using three wavebands with a relative rmse below 5 percent. The results are comparable to accuracies obtained in other studies. For instance, Mutanga & Skidmore (2004) mapped nitrogen concentrations in savanna grass with an rms error of 8.3 percent of the mean observed nitrogen concentration using continuum-removal. The portion of selected wavebands attributable to known substance absorption features strongly depends on the type of derivative spectra used. A method called “derivative of water removed spectra” (DWRS) produces the largest percentage of wavebands directly or indirectly related to known absorption features with laboratory and canopy spectra. Using band depth normalised spectra (BDN) the portion of wavebands attributable to known absorption features was relatively large with laboratory data but very low with HyMap spectra. Possibly, DWRS better than BDN preserves its ability to enhance absorption features during the upscaling from leaf to canopy spectra.

Predictive models obtained on the stand level (Figure 1) were applied on the HyMap image to compute maps of chlorophyll concentration and nitrogen concentration (not shown). Results of map overlay operations revealed coherence between C_{AB} and zones of stand development stage and between C_{AB} and zones of soil type. Larger values of C_{AB} occurred over soils with large base saturation (formed of basalt and colluvium) whereas poorly base saturated soils over sandstone showed lower C_{AB} values. However, the large variation in base saturation present in the soils at Gerolstein area is not equalled by corresponding variations in leaf nitrogen concentrations. From the low variation of nitrogen concentration present in Norway spruce needle at Gerolstein area no statement about the spatial variation of photosynthesis can be made. To increase variation in foliar nitrogen, the study has to be extended towards other ecosystems, such as deciduous forest, vine yards and orchards or grassland.

Acknowledgment

This research was financially supported by the German Research Community (DFG) and the research fund of Trier University. Forest stands were carefully selected with the help of Dr. W. Schwind, Gerolstein. The authors thank Samuel Bärish, Eva Pohl, Lena Lieckfeld (all Trier), Herr Mack (Trippstadt) and three woodmen for assistance during fieldwork at Gerolstein test site. Organisation of the flight campaign by Andreas Müller and Stefanie Holzwarth (DLR, Oberpfaffenhofen) is highly acknowledged.

References

- CURRAN, P. J. 1989: Remote sensing of foliar chemistry. *Remote Sensing of Environment*, 30: 271-278.
- CURRAN, P. J., DUNGAN, J. L., PETERSON, D. L. 2001: Estimating the foliar biochemical concentration of leaves with reflectance spectrometry - Testing the Kokaly and Clark methodologies. *Remote Sensing of Environment*, 76: 349-359.
- DEMETRIADES-SHAH T. H., STEVEN, M. D., CLARK, J. A. 1990: High resolution derivative spectra in remote sensing. *Remote Sensing of Environment*, 33: 55-64.
- GAO, B.-C. & GOETZ, A. F. H. 1994: Extraction of dry leaf spectral features from reflectance spectra of green vegetation. *Remote Sensing of Environment*, 47: 369-374.
- GAO, B.-C. & GOETZ, A. F. H. 1995: Retrieval of equivalent water thickness and information related to biochemical components of vegetation canopies from AVIRIS data. *Remote Sensing of Environment*, 52: 155-162.
- HILL, J. & MEHL, W. 2003: Georadiometrische Aufbereitung multi- und hyperspektraler Daten zur Erzeugung langjähriger kalibrierter Zeitreihen. *Photogrammetrie-Fernerkundung-Geoinformation*, 1/2003: 7-14.
- JOHNSON, L. F., HLAVKA, C. A., PETERSON, D. L. 1994: Multivariate analysis of AVIRIS data for canopy biochemical estimation along the Oregon transect. *Remote Sensing of Environment*, 47: 216-230.
- KOKALY, R. F. & CLARK, R. N. 1999: Spectroscopic determination of leaf biochemistry using band-depth analysis of absorption features and stepwise multiple linear regression. *Remote Sensing of Environment*, 67: 267-287.
- LICHTENTHALER, H. K. 1987: Chlorophylls and carotenoids, the pigments of the photosynthetic biomembranes. *Methods in Enzymology*, 148: 350-382.

- MUTANGA, O. & SKIDMORE, A. K. 2004: Integrating imaging spectroscopy and neural networks to map grass quality in the Kruger National Park, South Africa. *Remote Sensing of Environment*, 90: 104-115.
- SCHLÄPFER D., SCHAEPMAN M. E., ITTEN K. I. 1998: PARGE: Parametric Geocoding Based on GCP- Calibrated Auxiliary Data. *SPIE Int. Symp. on Opt. Sc., Eng. and Instr.* San Diego, CA: 334-344.
- SERRANO, L., PENUELAS, J., USTIN, S. L. 2002: Remote sensing of nitrogen and lignin in Mediterranean vegetation from AVIRIS data: Decomposing biochemical from structural signals. *Remote Sensing of Environment*, 81: 355-364.
- VITOUSEK, P. M. 1982: Nutrient cycling and nutrient use efficiency. *Nature*, 119: 553-572.
- WARING, R. H. & RUNNING, S. W. 1998: Forest ecosystems - Analysis at multiple scales. San Diego, London, Boston. Academic Press.
- WILSON, P. R. 1990: A new instrument concept for nitrogen / protein analysis - a challenge to the Kjeldahl method. *Aspects of Applied Biology*, 25: 443-446.
- ZARCO-TEJADA, P. J., MILLER, J. R., MORALES, A., BERJÓN, A., AGÜERA, J. 2004: Hyperspectral indices and model simulation for chlorophyll estimation in open-canopy tree crops. *Remote Sensing of Environment*, 90: 463-476.

Address:

Martin Schlerf, Behringstraße, Universität Trier, D-54286 Trier, Germany (E-mail: schlerf@uni-trier.de)