USING SPECTRAL INFORMATION AT THE NIR WATER ABSORPTION FEATURES TO ESTIMATE CANOPY WATER CONTENT AND BIOMASS

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ABSTRACT:

Biomass is one of the key biophysical variables of interest in vegetation studies and it can be defined in terms of fresh matter weight or dry matter weight. Biogeochemical processes, such as photosynthesis, evaporation and net primary production, are directly related to foliar water and are moreover commonly limited by water stress. Therefore, canopy water content is important for the understanding of the terrestrial ecosystem functioning. Spectral information related to the water absorption features at 970 nm and 1200 nm offer interesting possibilities for deriving information on leaf and canopy water content. In the present work, hyperspectral reflectance data representing a range of canopies were simulated at the leaf level using the PROSPECT model and at the canopy level using the combined PROSPECT+SAILH model. Derivative spectra close to the absorption features at about 970 nm and 1200 nm showed a strong predictive power for the leaf and canopy water content (CWC). Ratio indices defining the absorption features had a smaller predictive power. The feasibility of using information from the water absorption features in the near-infrared (NIR) region of the spectrum was tested by estimating CWC and biomass for two quite different test sites. The first site was a homogeneously managed agricultural field with a grass/clover mixture and with very little variation within the field. The other site was a very heterogeneous natural area in the floodplain Millingerwaard along the river Waal in the Netherlands. Spectral information at both test sites was obtained with an ASD FieldSpec spectrometer during the summer of 2004. At the Millingerwaard site also a flight with the HyMap airborne imaging spectrometer was performed. Individual spectral bands and traditional vegetation indices based on red and NIR spectral bands yielded moderate estimates for biomass and CWC. Ratio indices and the continuum removal method describing the absorption features yielded good results. Best results were obtained for the derivative spectra. Highest correlation with CWC was obtained for the derivative spectrum at about 950 nm, meaning at the slope of the first water absorption feature. Promising results in estimating CWC and biomass for various vegetation types were not only obtained for field spectroradiometer data, but also for airborne imaging spectrometer data, indicating the potential for upscaling to larger areas.

1. INTRODUCTION

For describing the relationship between spectral measurements and biophysical and –chemical variables of vegetation both statistical and physical approaches have been used. As an example of statistical methods, numerous vegetation indices (VIs) have been developed for estimating variables like biomass and leaf area index for a range of vegetation types (Broge and Leblanc, 2001; Daughtry *et al.*, 2000; Haboudane *et al.*, 2004; Haboudane *et al.*, 2002; Schlerf *et al.*, 2005; Thenkabail *et al.*, 2002). Physical-based methods often use radiative transfer (RT) models describing the interaction of radiation with the plant canopy based on physical principles. Subsequently, model inversion is used for estimating biophysical and -chemical properties of the canopy (Atzberger, 2004; Combal *et al.*, 2003; Jacquemoud *et al.*, 2000). However, due to the collinearity of spectral bands, particularly when making use of hyperspectral imagery, and due to the observation that numerous variations in different biophysical variables cause similar spectral differences, we have to deal with the ill-posed nature of the inversion (singular matrices). RT models are very suitable for studying the relationship between biophysical variables and reflectances or VIs. Subsequently, VIs may be used for estimation and prediction purposes, albeit that they often are only locally calibrated. The use of VIs also is the most common way to drastically reduce the dimensionality of a hyperspectral data set. A good index would be an index only sensitive to the variable of interest and not to other variables.

Biomass is one of the key biophysical variables of interest in vegetation studies (both cultivated and natural vegetation). Biomass can either be defined in terms of fresh matter weight or as dry matter weight. In addition, the canopy water content, being the difference between fresh and dry matter weight, is of interest in many applications. Biogeochemical processes, such as photosynthesis, evaporation and net primary production, are directly related to foliar water and are moreover commonly limited by water stress. Thus, canopy water content is important for the understanding of the terrestrial ecosystem functioning.

Water absorption features as a result of absorption by O-H bonds in water can be found at approximately 970, 1200, 1450 and 1950 nm (Curran, 1989). The features at 1450 and 1950 nm are most pronounced. However, in those spectral bands atmospheric absorption by water vapour is that strong that hardly any radiation is reaching the Earth surface. As a result, those bands will result in very noisy measurements and should not be used for remote sensing. The features at 970 and 1200 nm are not that pronounced, but still clearly observable (Danson *et al.*, 1992; Sims and Gamon, 2003). Therefore, these offer interesting possibilities for deriving information on leaf and canopy water content.

At the leaf level use is often made of the leaf water content in terms of the so-called equivalent water thickness (EWT), defined in quantity of water per unit leaf area in g.cm^{-2} (Danson *et al.*, 1992). At the canopy level the canopy water content (CWC) can be defined as the quantity of water per unit area of ground surface and thus is given in g.m^{-2} (Ceccato *et al.*, 2002):

$$CWC = LAI \times EWT \qquad (1)$$

Thus far, a limited number of studies have developed spectral indices using the water absorption bands at 970 and 1200 nm for estimation of canopy water content. Danson *et al*. (1992) showed that the first derivative of the reflectance spectrum corresponding to the slopes of the absorption feature provides better correlations with leaf water content than those obtained from the direct correlation with reflectance. Peñuelas *et al.* (1993) focused on the 950-970 nm region and defined the so-called water band index (WI):

$$WI = \frac{R_{900}}{R_{970}}, \qquad (2)$$

where R_{900} and R_{970} are the spectral reflectances at 900 and 970 nm, respectively.

Sims and Gamon (2003) generalized this water band index by using a varying wavelength in the denominator, thus testing the effect of a varying water absorption across the spectrum:

$$WI = \frac{R_{900}}{R_{XXX}}, \qquad (3)$$

where the reference wavelength is kept constant at 900 nm.

Gao (1996) defined the normalised difference water index (NDWI) as:

$$NDWI = \frac{(R_{860} - R_{1240})}{(R_{860} + R_{1240})}, \qquad (4)$$

where R_{860} and R_{1240} are the spectral reflectances at 860 and 1240 nm, respectively.

Finally, a continuum removal approach was applied to the two absorption features at about 970 and 1200 nm. This is a way of normalizing the reflectance spectra (Kokaly and Clark, 1999). The maximum band depth, the area under the continuum and the area normalized by the maximum band depth (ANMB) (Malenovský *et al.*, 2005) were applied for estimating biomass and CWC.

The objective of the present study is to compare different vegetation indices based on the water absorption features at 970 and 1200 nm in estimating biomass (fresh and dry matter) and the canopy water content. First, model simulations towards leaf and canopy water content are performed using the PROSPECT and SAILH radiative transfer models. Particularly the potential of various indices related to the water absorption features at 970 and 1200 nm is investigated. Subsequently, field spectroradiometer measurements obtained from two study sites (a cultivated grassland area and a natural area) are analysed. Finally, airborne HyMap data for the second test site are analysed.

2. MATERIAL AND METHODS

2.1 The Study Sites and Field Data

The first study site concerns a grassland field with a mixture of grass and white clover at the 'Droevendaal' experimental farm in Wageningen, the Netherlands. A total of 20 plots were defined within a 2.2 ha field. Plots were each 15 m long and 3 m wide and they were harvested using a plot-harvester on July 30th, 2004. Biomass (fresh weight) was determined with a built-in weighing unit on the harvester. Samples of the harvested material were oven dried for 72 hours at 70°C and dry matter weight as well as canopy water content was determined.

The second study site is a very heterogeneous natural area in the floodplain Millingerwaard along the river Waal in the Netherlands. This is a nature rehabilitation area, meaning that individual floodplains are taken out of agricultural production and are allowed to undergo natural succession. This has resulted in a heterogeneous landscape with river dunes along the river, a large softwood forest in the eastern part along the winter dike and in the intermediate area a mosaic pattern of different succession stages (pioneer, grassland, shrubs). Nature management (e.g., grazing) within the floodplain is aiming at improvement of biodiversity. Based on the available vegetation map of the area, 21 locations with specific vegetation structure types were selected. For each location a plot of 5 x 5 m was selected with a relatively homogeneous vegetation cover. Beginning of August 2004 vegetation biomass was sampled in three subplots per plot measuring 0.5 x 0.5 m. After drying for 24 hours at 70°C, vegetation dry matter weight was determined. Subsequently, the average dry biomass per plot was calculated. Unfortunately, no fresh weight was measured, so canopy water content could not be determined.

2.2 Field Spectroradiometer Measurements

July 29th, 2004, a field campaign with an ASD FieldSpec Pro FR spectroradiometer was performed at site 1 (Wageningen). The spectroradiometer was deployed using a fiber optic cable with a 25° field of view. Measurement height above the plot was about 1 – 1.5 m. As a result, the field of view at the plot level was circular with a radius ranging from 0.22 – 0.33 m. About 10 measurements per plot were performed, whereby each measurement represents the average of 50 readings at the same spot. The sampling interval was 1 nm. Calibration was done by using a Spectralon white reference panel.

July 28th, 2004, a field campaign with an ASD FieldSpec Pro FR spectroradiometer was performed at site 2 (Millingerwaard). For every plot 10 measurements were performed, whereby each measurement was the average of 15 readings at the same spot. Measurement height was about 1 m above the vegetation. A Spectralon white reference panel was used for calibration. For one location only sand was measured and not the vegetation. As a result, 20 plots remained for further analysis.

After calculating average spectra per plot, the resulting spectra were smoothed using a 10 nm wide moving Savitsky-Golay filter (applying a fourth order polynomial fit within the window) to reduce instrument noise.

2.3 Airborne Data

On July 28th, 2004, airborne imaging spectrometry data were collected using the HyMap sensor (Integrated Spectronics, Australia) onboard a Dornier DO-228 aircraft operated by the German Aerospace Centre DLR for test site 2 (Millingerwaard). A complete spectrum over the range of 450-2480 nm is recorded with a bandwidth of 15-20 nm by 4 spectrographic modules. Each module provides 32 spectral channels giving a total of 128 spectral measurements for each pixel. However, the delivered data contains 126 bands because the first and last bands of the first spectrometer are deleted during pre-processing. Ground resolution of the images is 5 m. The flight line was oriented close to the solar principal plane to minimize directional effects. The HyMap images were geo-atmospherically processed with the modules PARGE and ATCOR4 to obtain geocoded top-of-canopy reflectance data. Visibility was estimated by combining sun photometer measurements with Modtran4 radiative transfer simulation. Finally, spectral signatures were derived for the pixels matching the 21 plots defined in the field.

2.4 Reflectance Models

The PROSPECT model is a radiative transfer model for individual leaves. It simulates leaf spectral reflectance and leaf spectral transmittance as a function of leaf chlorophyll content (C_{ab}), equivalent leaf water thickness (EWT) and a leaf structure parameter (N). The most recent version of PROSPECT was used including leaf dry matter (C_m) as a simplification for the leaf biochemistry (protein, cellulose, lignin).

The one-layer SAILH radiative transfer model simulates canopy reflectance as a function of canopy parameters (leaf reflectance and transmittance, leaf area index and leaf inclination angle distribution), soil reflectance, ratio diffuse/direct irradiation and solar/view geometry (solar zenith angle, zenith view angle and sun-view azimuth angle). It was modified by taking the hot spot effect into account.

The output of the PROSPECT model can be used directly as input into the SAIL model. As a result, these models can be used as a combined PROSPECT-SAILH model. Simulations were performed at a 5 nm spectral sampling interval. Since the absorption features of leaf constituents are implemented in the PROSPECT model by means of look-up tables and not as continuous functions, simulated spectra have to be smoothed for calculating useful derivatives. Therefore, the simulated spectra were smoothed using a 30 nm wide moving Savitsky-Golay filter (applying a fourth order polynomial fit within the window).

In this paper we will not present an in-depth sensitivity analysis, but an exploratory analysis was carried out to study the effect of some of the main leaf and canopy variables on the estimation of leaf and canopy water content. The inputs for the PROSPECT simulations are shown in Table 1 and those for the combined PROSPECT-SAILH simulations are shown in Table 2.

PROSPECT parameters	Nominal values and range
Equivalent water thickness (EWT)	0.01 – 0.10 g. cm^{-2} (step of 0.01)
Dry matter (C_m)	0.005 / 0.010 / 0.015 $g.cm^{-2}$
Structural parameter (N)	1.0 / 1.8 / 2.5
Chlorophyll a+b (C_{ab})	40 $\mu g.cm^{-2}$

Table 1. Nominal values and range of parameters used for the leaf simulations with PROSPECT

SAILH parameters	Nominal values and range
Equivalent water thickness (EWT)	0.01 – 0.10 g. cm^{-2} (step of 0.01)
Dry matter (C_m)	0.005 $g.cm^{-2}$
Structural parameter (N)	1.8
Chlorophyll a+b (C_{ab})	40 $\mu g.cm^{-2}$
Leaf area index	0.5/ 1.0 / 1.5 / 2 / 3 / 4 / 5 / 6
Leaf angle distribution	Spherical / Planophile / Erectophile
Hot-spot parameter	0
Soil reflectance	0.20
Diffuse/direct radiation	0
Solar zenith angle	45°
Viewing angle	0° (nadir)
Sun-view azimuth angle	0°

Table 2. Nominal values and range of parameters used for the canopy simulations with the combined PROSPECT-SAILH model

3. RESULTS AND DISCUSSION

3.1 Model Simulations

The PROSPECT model simulations show that the leaf dry matter content and particularly the leaf structural parameter have a huge effect on the relationship between the spectral reflectance in the 900 – 1300 nm range and the equivalent water thickness (EWT). Due to this, individual spectral bands are not well correlated with EWT. However, when calculating the first derivative spectra the correlations increase dramatically. The derivatives at spectral regions close to the water absorption features at 970 and 1200 nm are mainly depending on the EWT and are hardly affected by the leaf structural parameter and the leaf dry matter content. As a result, derivatives are often well correlated with EWT (Figure 1). Region A in Figure 1 relates to the left shoulder of the absorption feature at about 970 nm. Region B relates to the right shoulder. Region C refers to the left shoulder of the absorption feature at about 1200 nm. The right shoulder of the latter absorption feature (region D) is less pronounced as simulated by PROSPECT, because it moves gradually into the left shoulder of the major absorption feature at 1450 nm (region E). Figure 2 provides the relationship between the derivative at 942.5 nm and EWT as an example. The first derivative outperformed ratio indices and the continuum removal method (results not shown).

Simulations with the combined PROSPECT-SAILH model show that the leaf angle distribution and particularly the LAI determine the spectral reflectance at the shoulders of the water absorption features. As a result, individual spectral bands are not well correlated with the canopy water content (CWC). They are most strongly correlated with the LAI. The first derivative spectra are highly correlated with LAI in the near-infrared up to a wavelength of about 900 nm. Beyond 900 nm the first derivative is much better correlated with CWC (Figure 3). High correlations are obtained at the shoulders of the water absorption features. The same regions with high coefficients of determination can be observed as at the leaf level (cf. Figure 1). Figure 4 shows an example of the relationship between the first derivative (at 942.5 nm) and CWC. Again the first derivative showed better results than the mentioned indices from literature.

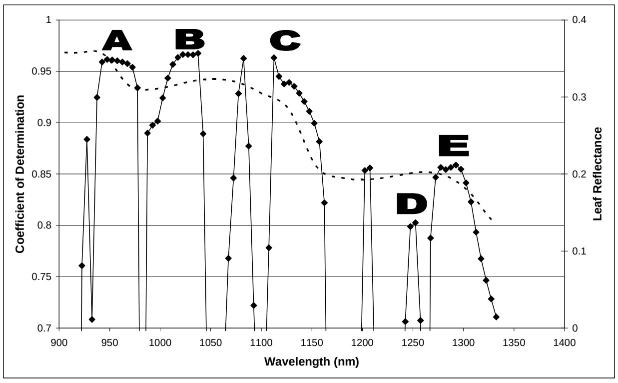

Figure 1. Coefficients of determination between equivalent water thickness and first derivative of leaf reflectance. The dotted line provides an example of a leaf reflectance signature (PROSPECT simulations)

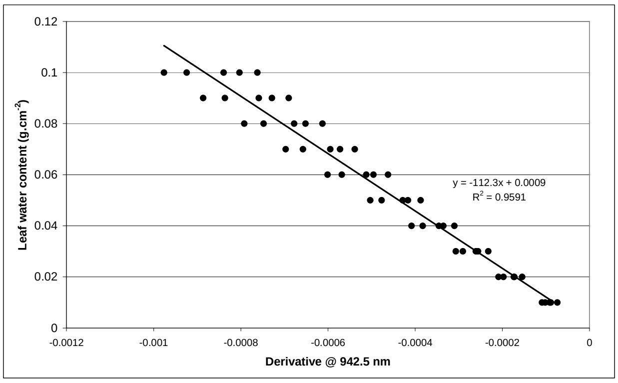

Figure 2. Relationship between first derivative of leaf reflectance at 942.5 nm and equivalent water thickness (PROSPECT simulations with various C_m and *N* values, cf. Table 1)

3.2 Test site 1: Wageningen

Using the field spectroradiometer measurements, we related the spectral reflectances with the field observations (fresh weight, dry weight and canopy water content). Figure 5 shows the coefficients of determination (R^2) between these three canopy biophysical variables and the spectral reflectances. The R^2 curves for fresh weight and canopy water content are very similar. Also dry weight shows a similar pattern, albeit that the R^2 values are somewhat lower. Notably maxima are observed around 937 nm (R^2 of 0.54 for CWC) and 1130 nm (R^2 of 0.48 for CWC). These spectral bands are located on the left shoulders of the two water absorption features at 970 and 1200 nm, respectively.

The first derivative spectra (Figure 6) show that R^2 values again were nearly the same for fresh weight and CWC, whereas those for dry weight were a bit lower. A high R^2 value at 944.5 nm is observed, being again the left shoulder of the 970 nm absorption feature. R^2 with CWC was 0.82. However, the R^2 varies strongly with wavelength. Also at the left shoulder of the 1200 nm feature a maximum in the derivative spectrum is observed. At 1134 nm the R^2 of the derivative with CWC was 0.69. Figure 7 illustrates the relationship between the first derivative at 944.5 nm and CWC. When the results of Figure 4 are presented in the same CWC units, we see that the simulated relationship fits very well with the one given in Figure 7.

The ratio-based indices and the indices based on the continuum-removal method perform worse than the first derivative, but better than the individual spectral bands.

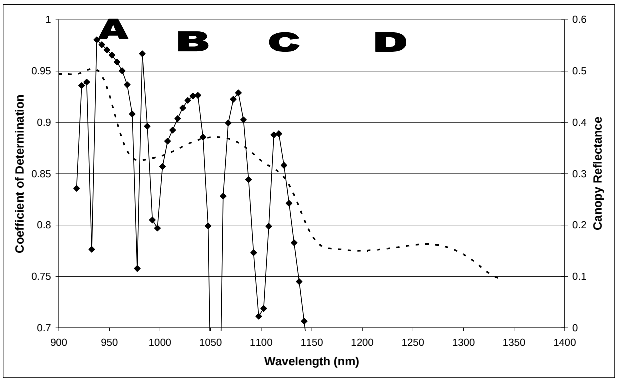

Figure 3. Coefficients of determination between canopy water content and first derivative of canopy reflectance. The dotted line provides an example of a canopy reflectance signature (PROSPECT-SAILH)

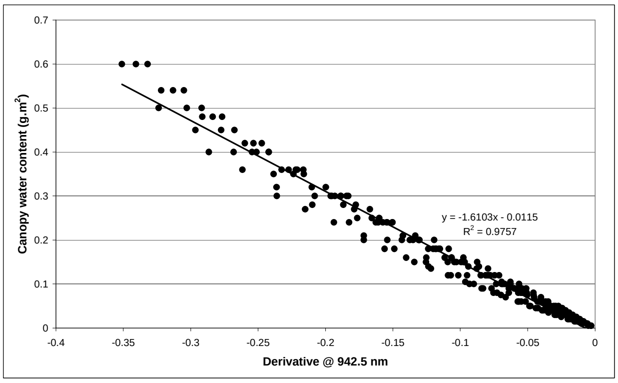

Figure 4. Relationship between first derivative of leaf reflectance at 942.5 nm and canopy water content (PROSPECT-SAILH simulations with various leaf angle distributions, cf. Table 2)

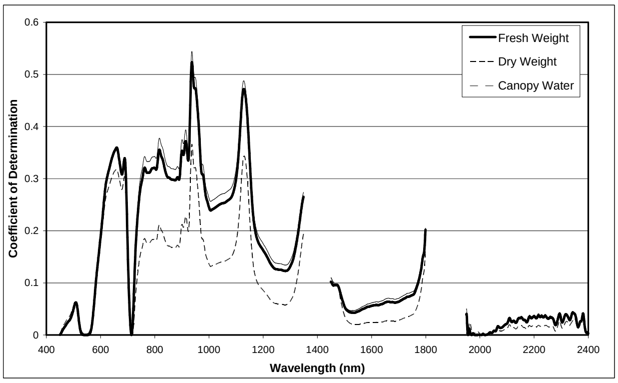

Figure 5. Coefficients of determination between canopy biophysical variables and FieldSpec canopy reflectance at the Wageningen test site

3.3 Test site 2: Millingerwaard

3.3.1 Field spectroradiometer data

For the Millingerwaard test site in 2004 only dry weight of samples was determined. Since fresh weight, dry weight and canopy water content are correlated, it makes sense to relate indices based on the water absorption features also with dry weight. Results for site 1 confirm their potential. Direct regressions of dry weight on individual spectral bands obtained from the field spectroradiometer yielded poor results. R^2 values for the first derivative spectra yielded much better results for

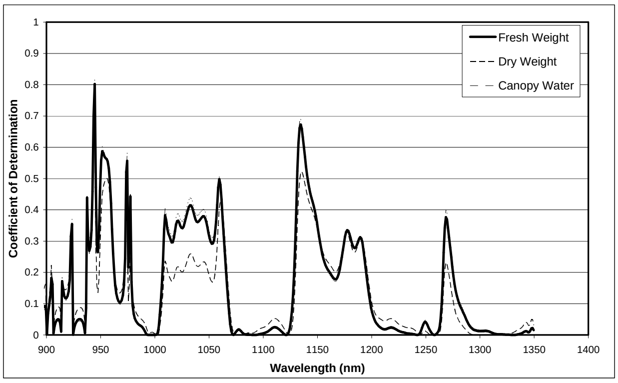

Figure 6. Coefficients of determination between canopy biophysical variables and first derivative of canopy reflectance at the Wageningen test site

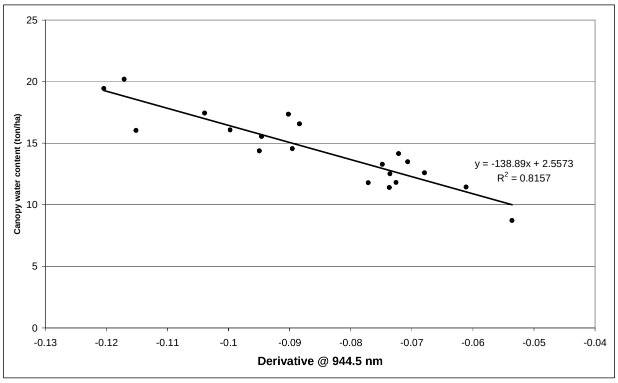

Figure 7. Relationship between first derivative of canopy reflectance at 944.5 nm and canopy water content at the Wageningen test site

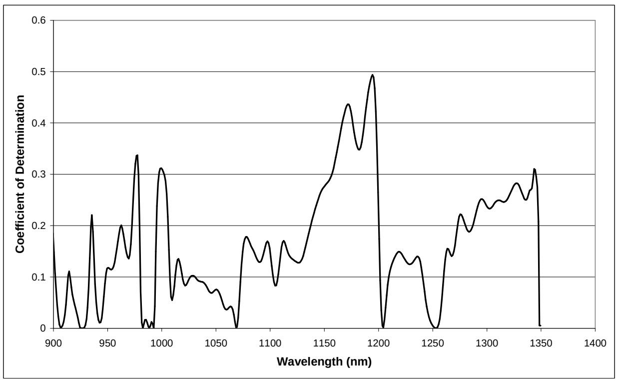

Figure 8. Coefficients of determination between canopy dry weight and first derivative of FieldSpec canopy reflectance at the Millingerwaard test site (16 plots)

this test site. Results were even slightly better when omitting four plots that were influenced by heavy grazing and as a result had a very low but dense grass sward (Figure 8).

In particular, the region at the left shoulder of the second absorption feature close to 1200 nm showed high R^2 values. At about 1170.5 nm the R^2 was 0.43, whereas at about 1194.5 nm this data set showed an R^2 value of 0.49 (based on 16 plots). However, the latter wavelength is already very close to the minimum in the spectrum due to the specific water absorption feature. At 935.5 nm the R^2 value showed a relative maximum, but the value was only 0.22. Due to the heterogeneous nature of the vegetation in the Millingerwaard, results are worse than for a homogeneous grassland parcel at the Wageningen site. Figure 9 shows the example of the relationship between the first derivative at 935.5 nm and dry weight.

Ratio-based indices do not provide a very good relationship with dry weight (best R^2 of 0.23).

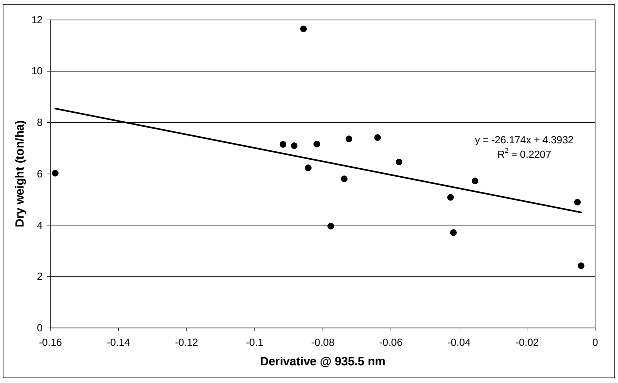

Figure 9. Relationship between first derivative of FieldSpec canopy reflectance at 935.5 nm and canopy dry weight at the Millingerwaard test site (16 plots)

3.3.2 Airborne data

Direct regressions of dry weight on individual spectral bands obtained from the HyMap imaging spectrometer also yielded poor results around the water absorption features. R^2 values for the first derivative spectra yielded better results for this test site, particularly when omitting the four plots that were influenced by heavy grazing as mentioned in the previous subsection (Figure 10).

In particular, the region at the right shoulder just after the first absorption dip at 970 nm and the one at the left shoulder of the second absorption feature showed high R^2 values. At about 1000 nm the R^2 was 0.51 and at about 1105 nm the R^2 was 0.50 (based on 17 plots). At 936 nm the R^2 value showed a relative maximum, but the value was only 0.36. Figure 11 shows this relationship between the first derivative at 936 nm and dry weight. This relationship is similar to the one obtained with the FieldSpec data (Figure 9).

Also the ratio-based indices based on the HyMap data do not provide a good relationship with dry weight (best R^2 of 0.28).

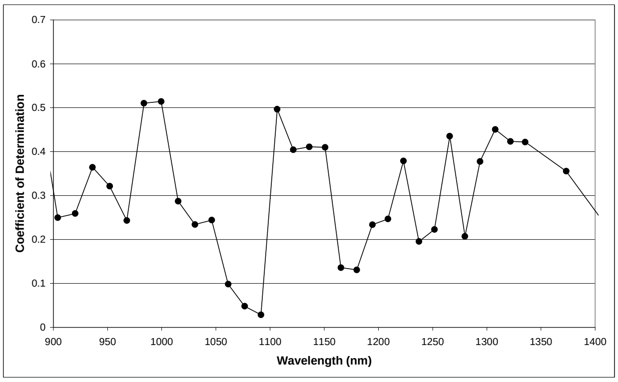

Figure 10. Coefficients of determination between canopy dry weight and first derivative of HyMap canopy reflectance at the Millingerwaard test site (17 plots)

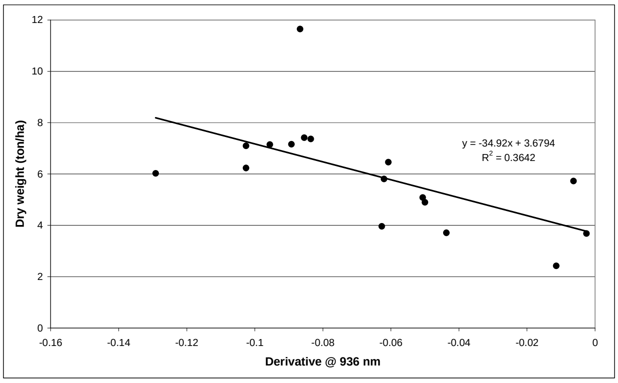

Figure 11. Relationship between first derivative of HyMap canopy reflectance at 936 nm and dry weight at the Millingerwaard test site (17 plots)

4. CONCLUSIONS

Results presented in this paper show that the spectral derivative for wavelengths on the slopes of the water absorption features at 970 nm and 1200 nm can be used for estimating canopy water content (CWC), fresh weight and dry weight. Model simulations show a good relationship between the derivative at 942.5 nm and CWC, which is not very sensitive for leaf and canopy structure. Field spectroscopic measurements on plots in a homogeneous grassland parcel confirm these results. For a nature area with many different plant species, results were less good, but still results show the potential of the derivative of the spectral reflectance at the shoulders of the mentioned water absorption features. Derivatives provide better results in this study than reflectances or indices as used in literature (Sims and Gamon, 2003).

This paper shows that results obtained at the leaf level can be upscaled to the canopy level using field spectroradiometers and subsequently to the regional level using airborne hyperspectral data.

REFERENCES

Atzberger, C., 2004. Object-based retrieval of biophysical canopy variables using artificial neural nets and radiative transfer models. *Remote Sensing of Environment*, 93(1-2), pp. 53-67.

Broge, N.H. and E. Leblanc, 2001. Comparing prediction power and stability of broadband and hyperspectral vegetation indices for estimation of green leaf area index and canopy chlorophyll density. *Remote Sensing of Environment*, 76(2), pp. 156-172.

Ceccato, P., N. Gobron, S. Flasse, B. Pinty and S. Tarantola, 2002. Designing a spectral index to estimate vegetation water content from remote sensing data: Part 1 - Theoretical approach. *Remote Sensing of Environment*, 82(2-3), pp. 188-197.

Combal, B., F. Baret, M. Weiss, A. Trubuil, D. Mace, A. Pragnere, R. Myneni, Y. Knyazikhin and L. Wang, 2003. Retrieval of canopy biophysical variables from bidirectional reflectance - Using prior information to solve the ill-posed inverse problem. *Remote Sensing of Environment*, 84(1), pp. 1-15.

Curran, P.J., 1989. Remote sensing of foliar chemistry. *Remote Sensing of Environment*, 30(3), pp. 271-278.

Danson, F.M., M.D. Steven, T.J. Malthus and J.A. Clark, 1992. High-Spectral Resolution Data for Determining Leaf Water-Content. *International Journal of Remote Sensing*, 13(3), pp. 461-470.

Daughtry, C.S.T., C.L. Walthall, M.S. Kim, E. Brown de Colstoun and J.E. McMurtrey III, 2000. Estimating corn leaf chlorophyll concentration from leaf and canopy reflectance. *Remote Sensing of Environment*, 74(2), pp. 229-239.

Gao, B.C., 1996. NDWI - A normalized difference water index for remote sensing of vegetation liquid water from space. *Remote Sensing of Environment*, 58(3), pp. 257-266.

Haboudane, D., J.R. Miller, E. Pattey, P.J. Zarco-Tejada and I.B. Strachan, 2004. Hyperspectral vegetation indices and novel algorithms for predicting green LAI of crop canopies: Modeling and validation in the context of precision agriculture. *Remote Sensing of Environment*, 90(3), pp. 337-352.

Haboudane, D., J.R. Miller, N. Tremblay, P.J. Zarco-Tejada and L. Dextraze, 2002. Integrated narrow-band vegetation indices for prediction of crop chlorophyll content for application to precision agriculture. *Remote Sensing of Environment*, 81(2-3), pp. 416-426.

Jacquemoud, S., C. Bacour, H. Poilve and J.P. Frangi, 2000. Comparison of four radiative transfer models to simulate plant canopies reflectance: Direct and inverse mode. *Remote Sensing of Environment*, 74(3), pp. 471-481.

Kokaly, R.F. and R.N. Clark, 1999. Spectroscopic determination of leaf biochemistry using band-depth analysis of absorption features and stepwise multiple linear regression. *Remote Sensing of Environment*, 67(3), pp. 267-287.

Malenovský, Z., C. Ufer, Z. Lhotáková, J.G.P.W. Clevers, M.E. Schaepman, P. Cudlín and J. Albrechtová, 2005. ANMB650-725 - A new optical index for chlorophyll estimation of a forest canopy from hyperspectral images. *Proceedings 4th EARSeL Workshop on Imaging Spectroscopy*, 27-29 April 2005, Warsaw, Poland, pp. 651-659.

Penuelas, J., I. Filella, C. Biel, L. Serrano and R. Save, 1993. The reflectance at the 950-970 nm region as an Indicator of plant water status. *International Journal of Remote Sensing*, 14(10), pp. 1887-1905.

Schlerf, M., C. Atzberger and J. Hill, 2005. Remote sensing of forest biophysical variables using HyMap imaging spectrometer data. *Remote Sensing of Environment*, 95(2), pp. 177-194.

Sims, D.A. and J.A. Gamon, 2003. Estimation of vegetation water content and photosynthetic tissue area from spectral reflectance: a comparison of indices based on liquid water and chlorophyll absorption features. *Remote Sensing of Environment*, 84(4), pp. 526-537.

Thenkabail, P.S., R.B. Smith and E. De Pauw, 2002. Evaluation of narrowband and broadband vegetation indices for determining optimal hyperspectral wavebands for agricultural crop characterization. *Photogrammetric Engineering and Remote Sensing*, 68(6), pp. 607-621.