ESTIMATING CANOPY WATER CONTENT USING IMAGING SPECTROSCOPY

Jan G.P.W. Clevers, Lammert Kooistra and Michael E. Schaepman

Wageningen University, Centre for Geo-Information, Wageningen, The Netherlands; e-mail: jan.clevers@wur.nl

ABSTRACT

Canopy water content (CWC) is important for the understanding of the functioning of the terrestrial ecosystem. Spectral information related to the water absorption features at 970 nm and 1200 nm offers interesting possibilities for deriving information on canopy water content. Hyperspectral reflectance data representing a range of canopies were simulated using the combined PROSPECT+SAILH model. Best results in estimating CWC were obtained by using spectral derivatives at the slopes of the 970 nm and 1200 nm water absorption features.

The feasibility of using information from the water absorption features in the near-infrared (NIR) region of the spectrum was tested by estimating canopy water content for a heterogeneous natural area in the floodplain Millingerwaard along the river Waal in the Netherlands. Spectral information was obtained with an ASD FieldSpec spectrometer and with the HyMap airborne imaging spectrometer during the summer of 2004. In 2005 a campaign with the FieldSpec and the AHS-160 airborne imaging spectrometer was performed.

Best results were again obtained for the derivative spectra. Highest correlation with CWC was obtained for the derivative spectrum at about 936 nm, meaning at the left slope of the first water absorption feature. Promising results were also obtained for the right slope of the 970 nm absorption feature. This is important since at the left slope one also has to take the influence of atmospheric water vapour absorption into account.

INTRODUCTION

Currently one of the main scientific issues is to understand and quantify the impact of global climate change on the Earth system. One of the challenges of the coming decades is the understanding of the role of terrestrial ecosystems and the changes they may undergo. The water cycle is one of its most important characteristics (i). In this respect, the canopy water content is of interest in many applications. Biogeochemical processes, such as photosynthesis, evaporation and net primary production, are directly related to foliar water. Thus, canopy water content is important for the understanding of the functioning of the terrestrial ecosystem.

Water absorption features for liquid water in plants can be found at approximately 970, 1200, 1450 and 1950 nm (ii). The features at 1450 and 1950 nm are most pronounced. However, at about 1400 and 1900 nm also broad absorption features occur due to water vapour in the atmosphere. As a result, hardly any radiation is reaching the Earth’s surface and, thus, the liquid water bands at 1450 and 1950 nm cannot be used. The features at 970 and 1200 nm are not that pronounced, but still clearly observable (iii,iv). Therefore, these offer interesting possibilities for deriving information on canopy water content. However, in these regions also minor absorption features due to atmospheric water vapour occur at 940 and 1140 nm (v). These are shifted somewhat to shorter wavelengths in comparison to the liquid water bands caused by water in the canopy. Figure 1 illustrates the position of the liquid water absorption features in the near-infrared (NIR) region for some spectral measurements on grassland plots (vi).
At the leaf level use is often made of the leaf water content in terms of the so-called equivalent water thickness (EWT), defined as the quantity of water per unit leaf area in g.cm\(^{-2}\). 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\(^{-2}\):

\[
CWC = LAI \times EWT
\]  

(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. (iii) 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. This was confirmed by Clevers and Kooistra (vi).

Peñuelas et al. (vii) focused on the 950-970 nm region and defined the so-called water band index (WI):

\[
WI = \frac{R_{900}}{R_{970}},
\]

(2)

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

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

\[
NDWI = \frac{(R_{860} - R_{1240})}{(R_{860} + R_{1240})},
\]

(3)

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

In a previous study (ix), we showed 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). This is illustrated in Figure 2. 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. In addition the influence of sun-viewing geometry seems to be minimal. 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 slopes of the mentioned water absorption features.

Figure 1: Example of two spectral signatures of grassland plots measured with the ASD FieldSpec Pro. The positions of the water absorption features at 970 nm and 1200 nm are indicated.
The objective of the present study is to upscale the field radiometer measurements using airborne hyperspectral data. Secondly, the derivative at the right slopes of the absorption features will be studied because they are not influenced by atmospheric water vapour.

![Figure 2: 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). This figure was published before in (ix).](image)

**MATERIAL AND METHODS**

**Study site and field data**

The 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 in 2004. 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. In order to make comparisons with other data sets, we assumed a dry matter content of 30% for all plots based on measurements done in 2005. Close study of biomass figures of all plots revealed one plot as an outlier. It had biomass figures that were more than 50% larger than those of the second highest. In spectral analyses the biomass figure of this plot showed to be an outlier all the time. Therefore, it was decided to omit this plot from further analysis. Preliminary analysis of the data also showed that four plots, which were influenced by heavy grazing and as a result had a very low but dense grass sward, had a deviating relationship between spectral indices and biomass (x). These were grouped as a distinct plant functional type. Omitting these from further analysis clearly improved results for 2004. This yielded 16 useful plots for further analysis.
In 2005, 12 locations with specific vegetation structure types were selected. For each location a plot of 20 x 20 m was selected with a relatively homogeneous vegetation cover. End of June 2005 vegetation fresh 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 and canopy water content were determined. Subsequently, the average canopy water content per plot was calculated.

**Reflectance models**

The PROSPECT model is a radiative transfer model for individual leaves (xi). 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 (xii) 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 (xiii).

The output of the PROSPECT model can be used directly as input into the SAILH 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 15 nm wide moving Savitsky-Golay filter (applying a second order polynomial fit within the window).

The inputs for the combined PROSPECT-SAILH simulations are shown in Table 1.

**Table 1: Nominal values and range of parameters used for the canopy simulations with the combined PROSPECT-SAILH model.**

<table>
<thead>
<tr>
<th>PROSPECT-SAILH parameters</th>
<th>Nominal values and range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalent water thickness (EWT)</td>
<td>0.01 – 0.10 g.cm$^{-2}$ (step of 0.01)</td>
</tr>
<tr>
<td>Dry matter ($C_m$)</td>
<td>0.005 / 0.010 / 0.015 g.cm$^{-2}$</td>
</tr>
<tr>
<td>Structural parameter ($N$)</td>
<td>1.0 / 1.8 / 2.5</td>
</tr>
<tr>
<td>Chlorophyll a+b ($C_{ab}$)</td>
<td>40 μg.cm$^{-2}$</td>
</tr>
<tr>
<td>Leaf area index</td>
<td>0.5 / 1.0 / 1.5 / 2 / 3 / 4 / 5 / 6</td>
</tr>
<tr>
<td>Leaf angle distribution</td>
<td>Spherical / Planophile / Erectophile</td>
</tr>
<tr>
<td>Hot-spot parameter</td>
<td>0 / 0.1</td>
</tr>
<tr>
<td>Soil reflectance</td>
<td>0.0 / 0.1 / 0.2</td>
</tr>
<tr>
<td>Diffuse/direct radiation</td>
<td>0</td>
</tr>
<tr>
<td>Solar zenith angle</td>
<td>15° / 30° / 45°</td>
</tr>
<tr>
<td>Viewing angle</td>
<td>-30° / 0° / 30°</td>
</tr>
<tr>
<td>Sun-view azimuth angle</td>
<td>0°</td>
</tr>
</tbody>
</table>

**FieldSpec measurements**

July 28th, 2004, a field campaign with an ASD FieldSpec Pro FR spectroradiometer was performed at the Millingerwaard site. Within a square area of 5 x 5 m centred at each plot 10 measurements were performed, whereby each measurement was the average of 15 readings at the same spot. So, the area for the spectral measurements (5 x 5 m) was larger than the one for the destructive sampling (2 x 2 m). Measurement height was about 1.5 m. Since vegetation height was varying for the various plant functional types, the distance between instrument aperture and canopy was vary-
ing. A Spectralon white reference panel was used for calibration. For one location only sand was measured and not the vegetation. Moreover, during measurements some cumulus clouds showed up in the direction of the sun. Since object measurements and reference measurements cannot be done simultaneously with the FieldSpec, it was decided to leave three suspect plots out of further analysis for the FieldSpec data. As a result, 13 plots remained.

June 19th, 2005, a field campaign with an ASD FieldSpec Pro FR spectroradiometer was performed at the Millingerwaard site. For every plot 12 measurements were performed according to the VALERI (VAlidation of Land European Remote sensing Instruments) sampling scheme (xiv), 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.

After calculating average spectra per plot, the resulting spectra were smoothed using a 15 nm wide moving Savitsky-Golay filter (applying a second order polynomial fit within the window) to reduce instrument noise.

**HyMap airborne measurements 2004**

On July 28th, 2004, airborne imaging spectrometry data were collected from an altitude of 2300 m (a.s.l.) using the HyMap sensor (Integrated Spectronics, Australia) onboard a Dornier DO-228 aircraft operated by the German Aerospace Centre DLR for the Millingerwaard site. 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 contain 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, approximating hemispherical directional reflectance factors (xv). 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.

**AHS airborne measurements 2005**

On June 19th, 2005, several flight strips were performed over the Millingerwaard test site with the Airborne Hyperspectral Scanner (AHS-160), operated by INTA (the Spanish National Institute for Aerospace Technology). The AHS-160 is a whiskbroom scanner with 63 bands in the reflective part of the EM spectrum and 17 bands in the thermal-infrared. The first 20 bands are in the VNIR range, band 21 is located at about 1620 nm, whereas bands 22 – 63 are located between 2.0 and 2.5 μm in the SWIR. For this study the first 20 bands in the 430 – 1030 nm region with a band width of about 30 nm are of interest. The first flight line, close to the solar principal plane, was analysed for this study. The flight was performed at an altitude of 1900 m (a.s.l.), resulting in a pixel size of 4.73 m (IFOV is 2.5 mrad). The images were geometrically coregistered with orthophotos obtained in 2004 at a spatial resolution of 1 m and using the Dutch National Coordinate system (RD) as a reference. The final pixel size was 5 m. Radiometric preprocessing and atmospheric correction of the image was performed at VITO (Flemish Institute for Technological Research) using a MODTRAN4 (xvi) and ATCOR4 (xvii) radiative transfer code and by using FieldSpec measurements performed in the field on reference targets (water, beach sand and asphalt) for iteratively improving the parameters describing the atmospheric composition (i.e. visibility, water vapour and aerosol type) for the whole image. However, checking the surface reflectances derived from the AHS image showed that the calibration was not that good. Therefore, an additional empirical line correction procedure was applied using the same reference targets. Finally, spectral signatures were derived using the GPS coordinates of the field plots by averaging over a 3 by 3 window (since the field plots were 20 by 20 m).
RESULTS AND DISCUSSION

Simulations PROSPECT-SAILH

As seen before (ix), the spectral derivatives for wavelengths on the slopes of the water absorption features at 970 nm and 1200 nm can be used for estimating the canopy water content (CWC). Best results are obtained for the left slope of the 970 nm feature (region A in Figure 2). Figure 2 shows that this slope is much steeper than the right slope (region B) as simulated by the PROSPECT-SAILH model. At the left slope of the 1200 nm absorption feature the models simulate an additional inflexion point, making it difficult to define a useful derivative on this slope. The right slope of the 1200 nm feature is not very pronounced. As found in a previous study, best results were obtained for the derivative at 942.5 nm. This is illustrated in Figure 3.

\[ y = -202.24x + 0.0437 \]
\[ R^2 = 0.9849 \]

Figure 3: Relationship between first derivative of canopy reflectance at 942.5 nm and canopy water content (PROSPECT-SAILH simulations with varying input parameters according to Table 1).

FieldSpec 2004

Figure 4 illustrates the correspondence between the spectral reflectance measured in 2004 with the FieldSpec and the one derived from the HyMap data for one of the plots with natural vegetation in the Millingerwaard. Since the HyMap derivative most close to the 942.5 nm wavelength (Figure 3) is the one at 936 nm, we illustrate the relationship between the derivative at 936.5 nm and CWC for the FieldSpec in Figure 5. At this wavelength we obtain an $R^2$ value of 0.72. This figure also shows that the relationship found for the FieldSpec (assuming a dry matter content of 30%) matches the simulated relationship of Figure 3 well. Figure 4 shows that the right slope of the 970 nm feature is much steeper than the one simulated with PROSPECT-SAILH. As a result, the derivative of the FieldSpec measurements in this region is not comparable to the one simulated with PROSPECT-SAILH, but at the same time it indicates the potential of using the derivative in this region. The advantage of using the right slope instead of the left slope of the 970 nm absorption feature is the reduced interference by absorption of atmospheric water vapour. Figure 6 illustrates the relationship between the derivative at 1031.5 nm (about halfway the right slope) and CWC, resulting into an $R^2$ value of 0.34.
Figure 4: Example of spectral signatures measured in 2004 with the FieldSpec and the HyMap sensor over a plot at the Millingerwaard test site.

Figure 5: Relationship between first derivative of FieldSpec canopy reflectance at 936.5 nm and canopy water content at the Millingerwaard test site in 2004. At the background the simulated relationship of Figure 3 is shown.
Figure 6: Relationship between first derivative of FieldSpec canopy reflectance at 1031.5 nm and canopy water content at the Millingerwaard test site in 2004.

HyMap 2004

Figure 4 shows that the radiometric and atmospheric calibration of the HyMap data yielded good results. The relationship between the derivative at 936 nm for HyMap and CWC is illustrated in Figure 7. This yields an $R^2$ value of 0.50. The range of derivatives is very similar to the one found for the FieldSpec (Figure 5) and the one simulated with PROSPECT-SAILH (Figure 3). The regression line is somewhat different, but this may be due to the small amount of data points used. Another reason may be the relatively wide spectral bands of HyMap. The result for the right slope of the 970 nm feature is illustrated in Figure 8 at 1030 nm. This is a wavelength similar to the one shown for the FieldSpec data in Figure 6. This resulted in an $R^2$ of 0.45 for the HyMap data, whereby the relationship was similar to the one for the FieldSpec data.

Figure 7: Relationship between first derivative of HyMap canopy reflectance at 936 nm and canopy water content at the Millingerwaard test site in 2004. At the background the simulated relationship of Figure 3 is shown.
FieldSpec 2005

Figure 9 illustrates the similarity of the spectral reflectances measured in 2005 with the FieldSpec and with the AHS sensor at the Millingerwaard test site. The relationship between the derivative at 936.5 nm and CWC for the 2005 FieldSpec data set is illustrated in Figure 10. This yields an $R^2$ value of 0.55. This relationship again is similar to the one found for the 2004 data sets and for the simulated data from PROSPECT-SAILH. The result for the derivative at the right slope of the 970 nm feature, specifically at 1031.5 nm, is illustrated in Figure 11. The $R^2$ observed is 0.43, which is quite similar to the values found at the same spectral position for the 2004 data sets.
Figure 10: Relationship between first derivative of FieldSpec canopy reflectance at 936.5 nm and canopy water content at the Millingerwaard test site in 2005. At the background the simulated relationship of Figure 3 is shown.

Figure 11: Relationship between first derivative of FieldSpec canopy reflectance at 1031.5 nm and canopy water content at the Millingerwaard test site in 2005.

AHS 2005

The calibration of the AHS sensor proved to be reliable after the empirical line correction when compared with FieldSpec measurements of the vegetation plots (Figure 9). Unfortunately, the spectral bands of the AHS sensor only range up to about 1000 nm in the VNIR region. Band 19 is precisely located at the 970 nm absorption feature. Due to the spectral band widths of about 30 nm (FWHM) the derivative between band 18 and 19 and the derivative between band 19 and 20 will not provide reliable indicators for respectively the left and the right slope of the 970 nm absorption feature. Therefore, the AHS only provides a useful derivative between band 17 and 18, with an average wavelength of about 933 nm. The relationship between the derivative at 933 nm and CWC
is illustrated in Figure 12 for the AHS data set. The resulting $R^2$ value is 0.56. Again, the observed relationship between the derivative and CWC is not very different from the ones obtained for the other data sets. Differences may be explained by different band positions and band widths.

![Graph showing the relationship between first derivative of AHS canopy reflectance at 933 nm and canopy water content at the Millingerwaard test site in 2005. At the background the simulated relationship of Figure 3 is shown.]

**Figure 12: Relationship between first derivative of AHS canopy reflectance at 933 nm and canopy water content at the Millingerwaard test site in 2005. At the background the simulated relationship of Figure 3 is shown.**

**CONCLUSIONS**

Results presented in this paper show that in particular the spectral derivative for wavelengths on the slope of the water absorption features at 970 nm can be used for estimating canopy water content (CWC). Earlier results (ix) obtained for model simulations and field spectroradiometer measurements (with a FieldSpec) are confirmed by airborne imaging spectrometry data. Best results are obtained for the left slope. The derivative of the spectral reflectance at about 936 nm for plots with natural vegetation at the Millingerwaard test site showed a similar relationship with CWC for a campaign with FieldSpec and airborne HyMap data in 2004 and for a campaign with FieldSpec and airborne AHS data in 2005. The relationship was also similar to the one simulated with a combined PROSPECT-SAILH model with a range of input parameters for these models.

A possible disadvantage of using the left slope of the 970 nm feature is the influence of atmospheric water vapour at about 940 nm (xviii). So, either one should take care of an accurate atmospheric correction when using the left slope or one can use the derivative at the right slope of the 970 nm absorption feature where the influence of atmospheric water vapour is negligible. Results for the Millingerwaard test site show promising results in this respect, for instance by using the derivative at about 1030 nm.

In a previous study it was shown that the derivatives provide better results in estimating CWC than water band indices as used in literature. These results are summarized in Table 2 together with the results of this paper.
Table 2: Results for the indices tested in estimating canopy water content as shown by the coefficient of determination ($R^2$) for the various data sets in this study.

<table>
<thead>
<tr>
<th></th>
<th>PROSPECT-SAILH</th>
<th>FieldSpec 2004</th>
<th>HyMap 2004</th>
<th>FieldSpec 2005</th>
<th>AHS 2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Derivative Left</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>slope</td>
<td>0.98@942.5 nm</td>
<td>0.72@936.5 nm</td>
<td>0.50@936 nm</td>
<td>0.55@936.5 nm</td>
<td>0.56@933 nm</td>
</tr>
<tr>
<td>Derivative Right</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>slope</td>
<td>0.93@1032.5 nm</td>
<td>0.34@1031.5 nm</td>
<td>0.45@1030 nm</td>
<td>0.43@1031.5 nm</td>
<td>--</td>
</tr>
<tr>
<td>WI</td>
<td>0.94</td>
<td>0.37</td>
<td>0.38</td>
<td>0.40</td>
<td>0.41</td>
</tr>
<tr>
<td>NDWI</td>
<td>0.86</td>
<td>0.50</td>
<td>0.25</td>
<td>0.36</td>
<td>--</td>
</tr>
</tbody>
</table>

ACKNOWLEDGEMENTS

The authors wish to acknowledge the Belgian Science Policy Office (BELSPO) for providing the HyMap and AHS data. VITO is acknowledged for organising the airborne campaigns and for preprocessing the AHS-160 images. DLR is acknowledged for acquiring and preprocessing the HyMap images in 2004, and INTEA for acquiring the AHS-160 images in 2005.

REFERENCES


