Estimating canopy water content using hyperspectral remote sensing data

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A B S T R A C T
Hyperspectral remote sensing has demonstrated great potential for accurate retrieval of canopy water content (CWC). This CWC is defined by the product of the leaf equivalent water thickness (EWT) and the leaf area index (LAI). In this paper, in particular the spectral information provided by the canopy water absorption feature at 970 nm for estimating and predicting CWC was studied using a modelling approach and in situ spectroradiometric measurements. The relationship of the first derivative at the right slope of the 970 nm water absorption feature with CWC was investigated with the PROSAIL radiative transfer model and tested for field spectroradiometer measurements on two test sites. The first site was a heterogeneous floodplain with natural vegetation like grasses and various shrubs. The second site was an extensively grazed fen meadow. PROSAIL simulations (using coupled SAIL/PROSPECT-5 models) showed a linear relationship between the first derivative over the 1015–1050 nm spectral interval and CWC \( R^2 = 0.97 \). For 8 plots at the floodplain site the spectral derivative over the 1015–1050 nm interval obtained with an ASD FieldSpec spectroradiometer yielded \( R^2 \) of 0.51 with CWC. For 40 plots at the fen meadow ASD FieldSpec spectral measurements yielded an \( R^2 \) of 0.68 for the derivative over the 1015–1050 nm interval with CWC. Consistency of the results confirmed the potential of using simulation results for calibrating the relationship between this first derivative and CWC.

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1. 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 is to understand the role of terrestrial ecosystems and the changes they may undergo. The water cycle is one of their most important characteristics (ESA, 2006). In this respect, the canopy water content is of interest, also in view of the water use efficiency of plants. In this paper, we focus on innovative approaches for retrieving canopy water content from optical remote sensing data, in particular hyperspectral data. To describe 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 indices have been developed for estimating leaf and canopy water (Cheng et al., 2008; Claudio et al., 2006; Colombo et al., 2008; Rodríguez-Pérez et al., 2007; Yilmaz et al., 2008; Zarco-Tejada et al., 2003). Radiative transfer (RT) models are highly suitable for studying the relationship between biophysical variables and reflectance or vegetation indices (VIs) and to study the effect of sources of variability (Atzberger, 2004; Combal et al., 2003; Jacquemoud et al., 2000). Subsequently, RT models may be used to determine ‘universal’ VIs that are site and species independent by calibrating VIs on large simulated datasets. A good index would be an index only sensitive to the variable of interest and not to other variables (cf. Verrelst et al., 2008).

Remote sensing techniques provide an integrated signal over the spatial resolution element of the detector. As a result, the canopy water content, being the amount of water per unit ground area, is a variable of interest. In RT models often the amount of water per unit leaf area, the so-called equivalent water thickness (EWT), is used (Hunt and Rock, 1989; Jacquemoud and Baret, 1990). By multiplying the EWT with the leaf area per unit ground area (called the leaf area index, LAI) the canopy water content (CWC) is obtained:

\[
\text{CWC} = \text{LAI} \times \text{EWT}
\]

(1)

In the field CWC can simply be determined as the difference between fresh weight (FW) and dry weight (DW):

\[
\text{CWC} = \text{FW} - \text{DW}
\]

(2)

Fig. 1 shows an example of RT simulation results (using PROSAIL, see Section 2.1) for a vegetation spectrum with three different CWC values. No simulation results are shown for the...
major atmospheric water absorption features around 1400 and 1900 nm, because these absorptions are such that hardly any solar radiation reaches the Earth’s surface at these wavelengths. As a result, these are not used in remote sensing of land surfaces. Fig. 1 shows that CWC in particular has an effect in the near-infrared (NIR) and the shortwave-infrared (SWIR) part of the spectrum. Fig. 1 also shows two water absorption features at approximately 970 and 1200 nm that are caused by the absorption by O–H bonds in liquid canopy water (Curran, 1989). Accurate measurements at these absorption features in the NIR are feasible with the increasing availability of hyperspectral images (Schaepman et al., 2009).

Analogously to using spectral derivatives at the slope of the red-edge region (680–800 nm) for chlorophyll estimation, spectral derivatives applied to the water absorption features at 970 and 1200 nm can be used for CWC estimation (Clevers et al., 2008). Danson et al. (1992) showed that the first derivative of the reflectance spectrum corresponding to the slopes of the absorption feature provides more significant correlations with leaf water content than those obtained from the direct correlation with reflectance. Rollin and Milton (1998) found moderate correlations between the first derivative at the left slope of both absorption features and CWC for a grassland site in the UK. Recently, Clevers et al. (2008) applied derivatives in a preliminary study at the field and at the airborne level. This latter study showed that spectral derivatives at the slopes of the 970 and 1200 nm absorption features have potential as predictors of CWC. The current paper presents the results of a follow-up study.

Clevers et al. (2008) showed that the first derivative of the reflectance spectrum at wavelengths corresponding to the left slope of the minor water absorption band at 970 nm was well correlated with CWC. PROSAIL model simulations showed that it was insensitive to differences in leaf and canopy structure, soil brightness and illumination and observation geometry. However, these wavelengths are located close to a water vapour absorption band at about 940 nm (Gao and Goetz, 1990). In order to avoid interference with absorption by atmospheric water vapour, the potential of estimating CWC using the first derivative at the right slope of the 970 nm absorption feature is studied in this paper. Results are compared with PROSAIL simulations, using a new, improved version of the PROSPECT model (Feret et al., 2008).

The main objective of the present study is to test the feasibility of a first derivative using the right slope of the 970 nm water absorption feature that could be used for estimating CWC, whilst not being influenced by other variables. In this way, this index will have general applicability. Radiative transfer model simulations were used for this purpose by using the PROSAIL model, based on a recalibrated version of the PROSPECT model (PROSPECT-5) as described by Feret et al. (2008) and using an extended spectral resolution of 1 nm (Le Maire et al., 2004). It will also be studied whether experimental results are comparable with simulated results by analysing spectroradiometer measurements obtained from two study sites in the Netherlands. If this is the case, PROSAIL simulations may be used for calibrating the relationship between the index and CWC.

2. Materials and methods

2.1. PROSAIL coupled radiative transfer model

PROSAIL is a combination of the PROSPECT leaf RT model (Jacquemoud and Baret, 1990) and the SAIL canopy RT model (Verhoef, 1984), which has been used extensively for a variety of applications (Jacquemoud et al., 2009). At the leaf level, PROSAIL uses leaf chlorophyll content (C_{ab}), equivalent leaf water thickness (EWT), leaf structure parameter (N) and leaf dry matter (C_{dm}) as inputs. At the canopy level, input parameters are LAI, leaf inclination angle distribution, soil brightness, ratio diffuse/direct irradiation, solar zenith angle, view zenith angle and Sun-view azimuth angle. It also includes a parameter describing the hot-spot effect (Kuusk, 1991). In a previous study (Clevers et al., 2008), an older version of PROSPECT (version 3) was used, simulating leaf reflectance and transmittance at a 5 nm spectral sampling interval. Recently, version 5 of PROSPECT has been released, performing simulations at a 1 nm spectral sampling interval and using updated values for the specific absorption coefficients of leaf constituents (Feret et al., 2008).

To study the relationship between derivatives and CWC (calculated from LAI and EWT), the effects of the main leaf and plant inputs on this relationship were studied. C_{ab} could be kept constant since it does not exhibit any effect beyond 800 nm. Since the specific absorption coefficient for dry matter is quite low and
Table 1
Nominal values and range of parameters used for the canopy simulations with the PROSAIL model.

<table>
<thead>
<tr>
<th>PROSAIL 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>Leaf dry matter (Cₘ)</td>
<td>0.002 g cm⁻²⁻¹</td>
</tr>
<tr>
<td>Leaf structure parameter (N)</td>
<td>1.0/1.8/2.5</td>
</tr>
<tr>
<td>Chlorophyll concentration (Cₐ)</td>
<td>40 μg cm⁻²⁻¹</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>0.0/0.1</td>
</tr>
<tr>
<td>Soil reflectance</td>
<td>Actual values</td>
</tr>
<tr>
<td>Diffuse/direct radiation</td>
<td>0</td>
</tr>
<tr>
<td>Solar zenith angle</td>
<td>0°</td>
</tr>
<tr>
<td>View zenith angle</td>
<td>0°</td>
</tr>
<tr>
<td>Sun-view azimuth angle</td>
<td>0°</td>
</tr>
</tbody>
</table>

※ Source: Jung et al. (2009).

constant below 1300 nm (Fourty et al., 1996), a constant value for Cₘ was used according to the findings of Jung et al. (2009) for a floodplain meadow. At the canopy level, the actual observation and solar angles of the experimental measurements (Section 2.3) were used. Also spectral soil brightness values were obtained from the actual experiments. The other inputs for the PROSAIL simulations varied according to the values given in Table 1.

Since the absorption features of leaf constituents are implemented in the PROSAIL model by means of look-up tables and not as continuous functions, simulated spectra have to be smoothed for calculating derivatives. The simulated spectra were smoothed using an 8 nm wide moving Savitsky-Golay filter applying a fourth-degree polynomial fit within the window according to the results of Le Maire et al. (2010). First, the modelling results were compared with experimental data collected in 2005 using a field spectroradiometer at a site with natural vegetation. This site was located in the floodplain Millingerwaard along the river Waal in the Netherlands (Kooistra et al., 2008; Schaepman et al., 2007). The site is a nature rehabilitation area allowed to undergo natural succession, which has resulted in a landscape with a pattern of different succession stages (pioneer vegetation, grassland, shrubs). Nature management within the floodplain aims to increase biodiversity. Based on the available vegetation map of the area, 12 homogeneous locations with specific vegetation structure types were selected. For each location a plot of 20 m × 20 m was selected with a relatively homogeneous vegetation cover. The size of these plots was chosen such that there also could be used as reference sites for an airborne hyperspectral campaign. End of June 2005 vegetation was sampled in three subplots per plot measuring 0.5 m × 0.5 m, by cutting all above-ground vegetation just above the surface. Since the sampling was very difficult and inaccurate for four plots with some larger shrubs, these plots were excluded from the current analysis. Vegetation fresh weight for every subplot was determined immediately after harvesting. After drying for 24 h at 70°C, vegetation dry weight and CWC were determined. Subsequently, the average CWC and its standard deviation per plot were calculated. The CV within plots ranged from 0.07 up to 0.57 with an average CWC over all plots of 0.53 kg m⁻².

2.3. Field spectroradiometry

On 19th June 2005, all plots of the heterogeneous floodplain (site 1) were measured with an ASD FieldSpec Pro FR spectroradiometer. Nadir measurements were performed between 11 and 15 h local time, resulting in a solar zenith angle varying between 30° and 40°. Meteorological observations showed a ratio of diffuse over direct irradiation of 5%. At every plot 12 measurements were performed according to the VALIDation of Land European Remote Sensing Instruments (VALERI) sampling scheme (Morisette et al., 2006). Measurement height was about 1.5 m above the vegetation and the instrument field-of-view was 25°. As a result, at the plot level a circular area of about 0.35 m² was measured. A Spectralon white reference panel was used for calibration and such calibration measurements were performed before and after measuring every plot. If necessary, instrument gain settings were adapted. Spectroradiometric measurements at the ground are hardly possible if larger shrubs are present within the field-of-view. As stated before, such plots were excluded in the analysis.

Site 2 was measured with the ASD FieldSpec on 9th and 10th June 2008. Measurement conditions were similar to those in 2005 (same range of solar angles). All subplots of all 40 plots were measured before harvesting the biomass. Measurement height above the plot was again 1.5 m and the same calibration procedure was followed as at site 1.

3. Results and discussion

3.1. PROSAIL simulations

The PROSAIL simulations were used to relate spectral derivatives to CWC. Since fitting non-linear relationships did not significantly increase accuracy over fitting linear ones, results of the linear relationships were only presented together with their coefficients of determination (R²).

Preliminary results of a sensitivity analysis between CWC and spectral derivatives have already been presented in a previous paper (Clevers et al., 2008). In particular, the influence of varying leaf parameters (dry matter, structure parameter and chlorophyll content) and of varying canopy parameters (LAI and leaf angle distribution) was tested. Results showed most significant relationships for the spectral derivatives. In particular, first derivatives at the left and at the right slopes of the 900 nm absorption feature and at the left slope of the 1200 nm absorption feature were significantly correlated with CWC. These results are confirmed by the simulation results obtained with the improved PROSAIL model (using PROSPECT-5) using a 1 nm spectral sampling interval. As in Clevers et al. (2008) simulations with the PROSAIL model showed that for many spectral positions beyond 900 nm the relationship between the first derivative and CWC is statistically significant at p < 0.001. In addition to the left slope of the 970 nm water absorption feature, also relationships at the right slope of this feature and at the left slope of the 1200 nm feature are highly significant (Fig. 2). In this paper, focus is on the right slope of the 970 nm absorption feature, because there no influence of absorption by atmospheric water vapour is expected. Fig. 2 shows that the reflectance at this right slope is increasing gradually and

...
that the \( R^2 \) for the relationship between the first derivative of adjacent wavelengths and CWC is rather constant. Therefore, we may calculate the first derivative over a wider interval, making the choice of wavelengths for derivative calculation less critical and making the derivative calculation more robust. Experimental results later in this paper suggest that an interval between 1015 and 1050 nm is a good choice. Fig. 3 provides the relationship between the first derivative over the 1015–1050 nm interval and CWC for variations in model input parameters as given in Table 1. There is an offset for the linear regression line because soil reflectance was not constant over the spectral interval. Field measurements at both test sites yielded a reflectance of 0.39 at 1015 nm and a reflectance of 0.40 at 1050 nm. Largest scatter around the linear regression line visible in Fig. 3 is caused by the variation in leaf inclination angle distribution. In the next section it will be tested whether this simulated relationship matches the one found with experimental data.

3.2. Millingerwaard site

For the Millingerwaard test site only eight plots remained for the analysis after removing the erroneous measurements for plots including tall shrubs. Fig. 4 shows the \( R^2 \)-values for the relationship between spectral derivatives and CWC. The result looks spiky, meaning that the \( R^2 \)-value depends on the exact position of the wavelengths used for calculating the derivative. The relationship between first derivative at the right slope of the 970 nm absorption feature and CWC yields a rather constant value for \( R^2 \). However, not the highest values are obtained at this right slope. In the 1015–1050 nm interval \( R^2 \) is about 0.5, which is significant at \( p < 0.05 \). This result confirms the finding with the simulated results (Section 3.1) that the exact position of the wavelengths used for calculating the first derivative at the right slope is not that critical.

Fig. 5 illustrates the relationship between the first derivative over the 1015–1050 nm interval and CWC. This yields an \( R^2 \)-value
of 0.51 (significant at \( p < 0.05 \)). The predictive power of the first derivative as index for estimating CWC was assessed by estimating the root mean square error of prediction (RMSEP) using the leave-one-out cross-validation approach. For the Millingerwaard site this resulted in a RMSEP of 0.34 kg m\(^{-2}\) (as relative to an average CWC of 0.95 kg m\(^{-2}\)). The relationship is in agreement with the one found for the simulated data from PROSAIL in Fig. 3. The latter simulation results are plotted at the background of the Millingerwaard results in Fig. 5. Due to the heterogeneous nature of the vegetation in the Millingerwaard site, results for some plots deviate from the simulated results. These plots contain taller herbs (up to about 1 m), making the spectroscopic measurements less accurate for small sampling areas.

3.3. Achterhoek site

The Achterhoek site also shows a varying species composition, but the vertical distribution of the canopy is not as extended and heterogeneous as for the Millingerwaard test site. Moreover, the number of plots (40) is much larger at the Achterhoek site. Fig. 6 shows the \( R^2 \)-values for the relationship between spectral derivatives and CWC. The \( R^2 \) for the 1015–1050 nm interval again is constant for this test site. It is lower than the best value at the left slope, but the observed values above 0.65 are statistically significant at \( p < 0.001 \). The \( R^2 \) at the right slope over the 1015–1050 nm interval is 0.68 (Fig. 7). The calculated RMSEP is 0.21 kg m\(^{-2}\) (as relative to an average CWC of 0.53 kg m\(^{-2}\)). The relationship again is in agreement with the one found for the simulated data from PROSAIL in Fig. 3, which are plotted at the background of the Achterhoek results in Fig. 7. In general, this site yields more accurate results than the Millingerwaard site, which can mainly be explained by the larger number of samples available for this site and a maximum vegetation height of about 0.5 m enabling accurate spectral measurements with the ASD FieldSpec spectroradiometer.
The agreement between the experimental data and PROSAIL is good when using reflectance derivatives over the 1015–1050 nm interval for both the Millingerwaard and the Achterhoek sites. Therefore, the relationship between first derivative and CWC was trained with PROSAIL and then this relationship was applied on the experimental data. The calibrated relationship is given in Fig. 3. When applying this relationship to the experimental data of the Millingerwaard site and then comparing the predicted values with those obtained from the ASD FieldSpec measurements, the RMSEP is 0.33 kg m\(^{-2}\). This value is about equal to the RMSEP value of 0.34 kg m\(^{-2}\) obtained for the experimental data themselves using the leave-one-out method (Fig. 5). Using the simulated relationship depicted in Fig. 3 for independently predicting the CWC for the Achterhoek site results in an RMSEP of 0.25 kg m\(^{-2}\). This value should be compared with an RMSEP of 0.21 kg m\(^{-2}\) as obtained for the experimental data only.

### 3.4. Calibration on simulated PROSAIL data

![Fig. 6. Coefficients of determination between CWC and first derivative of canopy reflectance as measured with the ASD FieldSpec at the Achterhoek site in 2008. The dotted line provides an example of a measured canopy reflectance signature.](image)

Results presented in this paper show that the spectral derivatives for wavelengths on the right slope of the water absorption feature at 970 nm can be used for estimating canopy water content (CWC). PROSAIL model simulations were performed using the improved PROSPECT-5 model as described by Feret et al. (2008). A linear relationship between first derivative over the 1015–1050 nm spectral interval and CWC was found, which was not very sensitive for leaf and canopy structure. Field spectroscopic measurements at two test sites, a floodplain with natural grasses and herbs and a fen meadow, confirmed the simulation results. The relationship between the first derivative over the 1015–1050 nm interval and CWC based on in situ spectral measurements obtained in the field appeared to match the simulated relationship obtained from the PROSAIL model. This showed that one may transfer simulated results to real measurements obtained in the field for various vegetation conditions.

### 4. Conclusions

Results presented in this paper show that the spectral derivatives for wavelengths on the right slope of the water absorption feature at 970 nm can be used for estimating canopy water content (CWC). PROSAIL model simulations were performed using the improved PROSPECT-5 model as described by Feret et al. (2008). A linear relationship between first derivative over the 1015–1050 nm spectral interval and CWC was found, which was not very sensitive for leaf and canopy structure. Field spectroscopic measurements at two test sites, a floodplain with natural grasses and herbs and a fen meadow, confirmed the simulation results. The relationship between the first derivative over the 1015–1050 nm interval and CWC based on in situ spectral measurements obtained in the field appeared to match the simulated relationship obtained from the PROSAIL model. This showed that one may transfer simulated results to real measurements obtained in the field for various vegetation conditions.
types, thus giving them a physical basis and more general applicability.

Both simulated and experimental FieldSpec spectra showed that the right slope of the 970 nm absorption feature is linear (constant) in the range from about 1015 nm up to about 1050 nm. Due to this broad interval, the first derivative over this 1015–1050 nm interval can be measured more accurately than the derivative at a certain spectral position (or narrow interval). As a result, this derivative also is more robust and less susceptible to noise. Smoothing the spectral measurements did not give better results than non-smoothed measurements. Smoothing was necessary when using narrow intervals (Clevers et al., 2008).

The PROSAIL simulations performed in this study do not include an atmospheric model. When using remote sensing observations from an airborne or spaceborne platform, one should also consider the water vapour absorption by the atmosphere. This occurs, for instance, at 940 and 1140 nm (Gao and Goetz, 1990; Iqbal, 1983), thus being shifted to shorter wavelengths as compared to the corresponding liquid water absorption features. This means that the effect of water vapour absorptions in the atmosphere occurs at the left slopes of the water absorption features used for estimating CWC. So, if one cannot correct well for the effects of atmospheric water vapour, it is recommended to use the first derivative, e.g., in the 1015–1050 nm interval.

Future work will continue focusing on higher spectral resolution instruments, in particular at the water absorption regions at 970 and 1200 nm. Instruments with a significantly higher spectral resolution would be able to assess separately water molecules in atmosphere and vegetation, allowing correct estimations for both atmospheric water vapour and liquid water in vegetation. Given recent advances in imaging spectrometer design, the top-of-canopy concept will be further challenged due to inherent scattering of atmospheric water in elevated canopies (such as forests).

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