Vegetation water content at 970 nm: Estimation using hyperspectral vegetation indices

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Abstract
This study takes advantage of the water absorption feature at 970 nm that is visible on the vegetation spectrum using hyperspectral field data. The downward deflection feature at 970 nm is not very pronounced but recognizable and can be used to estimate remotely the canopy water content. The individual performance of a number of existing vegetation water content (VWC) indices against the 970 nm absorption are assessed using linear regression model to establish relationships. Even so with the availability of existing VWC indices, such as the WBI and NDWI, using combinations of these indices for estimation have received limited consideration for vegetation studies. Merging indices while drawing attention to the absorption feature and boosting the weak liquid absorption band, is developed to maximize the sensitivity of the water index to VWC. The new Combined Vegetation Water Index (CVWI) showed a promise in assessing the vegetation water status derived from the 970 nm absorption wavelength. The results showed the CVWI was able to differentiate two groups of water content (WC) when regressed against the absorption feature – one coming from vegetation, the other from soil influence. Other water content indices failed to detect this. With a significant relationship observed in the cross-validation procedure (R^2 = 0.46, RMSE = 0.013), results suggest that CVWI can become a potential indicator of vegetation liquid water at 970 nm.

Keywords: vegetation water content, hyperspectral analysis, 970 nm, Combined Vegetation Water Index, CVWI

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1. Introduction

The canopy water content is of interest in many applications (Rollin and Milton, 1998; Zarco-Tejada et al., 2003; Jackson et al., 2004). For instance, biochemical processes, such as photosynthesis, evaporation and net primary production, are directly related to foliar water and are furthermore frequently limited by water stress (Serrano et al., 2000). Canopy water content is imperative for the understanding of the terrestrial ecosystem functioning.

Water absorption features for liquid water can be found at approximately 970, 1200, 1450, and 1950 nm in a vegetation spectrum (Carter, 1991; Kokaly and Clark, 1999; Tian et al., 2001). In most cases, the features at 1450 and 1950 nm are the most pronounced. However, at about 1400 and 1900 nm broad absorption also occurs due to water vapor in the atmosphere. As a result, hardly any radiation is reaching the Earth's surface and therefore, the liquid water bands at 1450 and 1950 nm cannot be used.

The downward deflection feature at 970 and 1200 nm are not that pronounced but still visibly recognizable. Gao and Goetz (1995) illustrated the presence of these liquid absorption features using the AVIRIS spectra. Accordingly, these spectral positions offer interesting possibilities for deriving information on canopy water contents.

This study applied a technique called continuum-removal (CR), a method of normalizing the reflectance spectra Clark and Roush (1984) suggested this technique to remove absorption features of no interest and highlight specific wavelength absorptions of interest. Kokaly and Clark (1999) used CR analysis to estimate nitrogen concentrations and results were very encouraging. Curran et al. (2001) used the method and tested it against the standard derivative analysis. The CR analysis produced higher R^2 values than the derivative method. Here, the technique is applied to the water absorption feature at the 970 nm of the vegetation spectra.

Since 2004, field spectroscopy campaigns have been performed at the University of Nebraska's Barta Brothers Ranch near Rose in the eastern Nebraska Sandhills. Field spectrometer measurements were acquired over plots with natural vegetation.

For this study, we utilize the continuum-removed-derived absorption values at 970 nm from the hyperspectral field data as a baseline for estimating the canopy water content. We aim to assess how well existing vegetation water content indices that are applicable to the contiguous bands behave to the values derived using CR approach at the 970 nm absorption channel.

Even with the availability of existing VWC indices, using combinations of these indices for estimation have received limited consideration for vegetation studies. Merging indices while drawing attention to the absorption feature and boosting the weak liquid absorption band can be developed to maximize the sensitivity of the water indices to VWC. Thus, another objective of the study is to transform index equations and introduce them against the absorption feature. Furthermore, we seek to assess the behavior of a new and adjusted index as a potential indicator of liquid water at 970 nm.

2. Materials and Methods

Study Area

The Sandhills of Nebraska is a unique ecosystem that covers 50,176 square kilometers of grass-covered sand dunes and 5,260 square kilometers of wetlands (Turner and Rundquist, 1980). The relationship between the land, water, wildlife, and people is what makes the Sandhills a truly unique place.

Spectral Measurements

The field dataset consisted of non-destructive spectral measurements that were measured under clear skies from vegetation and soil plots with 20 stations each using the Ocean Optics USB2000 spectrometer that covers the 350 nm to the 1025 nm wavelength range. The spectrometer provides resolution to 0.35 nm full width at half maximum (FWHM). Full details of the equipment can be found at the Ocean Optics website (oceanoptics.com). For this study, plots 2, 3, 6 and 8 were utilized. Perennial grasses and numerous weeds dominated these plots. In each sampling station, four readings were taken representing the cardinal directions. To prevent shadow directly over the samples, the operator was made to stand with the sun in front.

Spectra Pre-processing

All field spectra went through filtering to attenuate sensor noise. A moving average with a frame size of 7 points was applied. This corresponds to about 2 nm difference (VIS) and less than 2 nm (NIR) between beginning and ending points. The smoothing procedure on the high spectral resolution data did not only attenuate noise, but also define the structure of the absorption features.

The 970 nm Absorption Feature

The absorption feature at the water absorption wavelength, 970 nm, was derived using the SAMS software (Spectral Analysis and Management System developed by the Center for Spatial Technologies and Remote Sensing at the University of California, Davis). SAMS calculates areas based on the continuum removed principle. The absorption feature equation (eq. 1) is the ratio between the area under the function (in a specified spectrum interval) and the area under the straight line connecting the maxima.

$$a = 1 - \frac{Au}{Ac} \qquad [1]$$

where:
a = the absorption feature
Au = area under the curve
Ac = area under the continuum line

The feature around 970 nm is the only absorption feature for liquid water available for the hyperspectral field dataset.

Water Band Index

The Water Band Index (WBI) is a simple ratio index that uses R900 and R970 (Penuelas et al., 1997; Sims and Gamon, 2003; Serrano et al., 2000). Penuelas et al. (1993) showed that the ratio between the reflectance at a reference wavelength, 900nm, and the reflectance at 970 nm (water absorption band) closely tracked the changes in plant and canopy water content. The 900 nm is close to the absorption wavelength that makes the WBI much less sensitive to other factors such as geometry (Bull, 1991).

R900 and R970 were computed individually from three bands surrounding each of the 900 nm and 970 nm wavelength. The ratio of 900nm to 970nm (eq. 2) was employed to compute the WBI.

$$WBI = R900 / R970 \qquad [2]$$

Normalized Difference Water Index

The Normalized Difference Water Index (NDWI) developed by Gao (1996) and mentioned by Serrano et al. (2000) and Zarco-Tejada et al. (2003) was applied to the dataset. Serrano et al. (2000) found the NDWI to be sensitive to the variations of VWC (R^2=0.88), together with the WBI (R^2=0.86).

$$NDWI = \frac{(R857 - R1240)}{(R857 + R1240)} \qquad [3]$$

$$NDWI_R = \frac{(R857 - R970)}{(R857 + R970)} \qquad [4]$$

The NDWI equation, which employs the NIR and SWIR channels (eq. 3), was slightly revised to accommodate the bands only available for the hyperspectral data (eq. 4). Instead of utilizing the 1200 nm liquid absorption band, the 970 nm was used. The reference wavelength, 857 nm, was retained to account for the variation of leaf internal structure and dry matter content variations. The substitution of bands is expected to cause the sensitivity of the NDWI to VWC to diminish at a certain level. However, a relationship may still exist.

The use of the SWIR channel, specifically the 1200 nm, in the NDWI was tested by Ceccato et al. (2002) using SPOT-vegetation sensor. They concluded that the SWIR was critical to estimating VWC and that the contrast between the SWIR and NIR was sensitive to the mass and volume of vegetation water.

The modification of the NDWI followed the line of thinking of Bull (1991) that argued on the use of the 970 nm for VWC. The sensitivity of the spectral trough at 970 nm seems to be due to the great penetration of radiation of 970 nm into the canopy, giving reflectance readings that are more dependent on the total moisture content. According to the same author, the penetration is higher than in other longer wavelengths. Bull (1991) and Penuelas (1996) remarked on using radiation that is more weakly absorbed than in higher wavelengths, especially for moisture content gradients that are highly variable, as this penetrates more deeply into the vegetation. They concluded that the liquid water absorption bands at 970 nm and 1200 nm provided better correlations with water content than those of their counterparts at the longer wavelength.

Normalized Difference Vegetation Index

The Normalized Difference Vegetation Index (NDVI) was used by Tucker (1979) to estimate leaf water content and other physiological variables for grasses. The index was developed by Rouse et al. (1973), which utilizes the RED and NIR channels (eq. 5).

$$NDVI = \frac{(NIR - \mathrm{Re}\,d)}{(NIR + \mathrm{Re}\,d)} \qquad [5]$$

NDVI can be used to retrieve VWC as shown by Ceccato et al. (2002). The paper highlights the limitations of correlating NDVI with VWC, also mentioned by Jackson et al. (2004). Aside from the NDVI saturating at intermediate values of VWC, thus it is not responsive to full range of canopy water content, few more others were mentioned, such as the individual plant species has its own relationships of chlorophyll content and VWC, a decrease in Chl does not imply a decrease in VWC, and a decrease in VWC does not imply a decrease in Chl content.

Roberts et al. (1997) found a high degree of correlation between NDVI and liquid water, up to R^2=0.92. However, he cautioned the use of the NDVI as the temporal patterns contradicted the trends of liquid water for differing amount of vegetation cover.

Combined Index for VWC Detection

To avoid huge values, the difference of the inverse of R900 and R970 was taken and multiplied to the square of the inverse of the NDWI. The resulting combination was multiplied to the inverse of the WBI. The Combined VW Index (CVWI) is shown in equation 6:

$$CVWI = \frac{(R970 - R900)(R857 + R970)^2}{(R857 - R970)^2\, R900 R970}\left(\frac{R970}{R900}\right)^{1+n} \qquad \text{Eq. 6}$$

The index combination could enhance the absorption feature at 970 nm. Highlighting the reflectance at the water band wavelength in the equation could improve the index capability to correlate with the absorption feature.

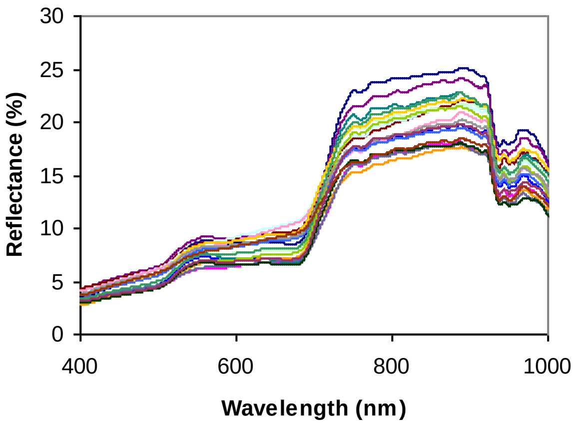
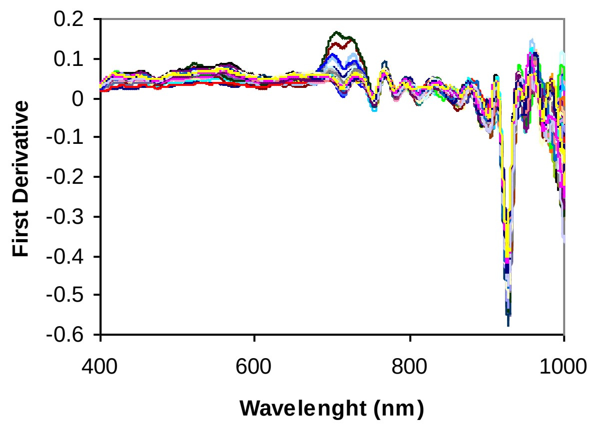


Figure 1: Vegetation canopy reflectance (le



3. Results and Discussion

The reflectance curves of few of the sampl
The absorption feature around the 970 nm
pre-processing. It is observed that son
demonstrated the characteristics of soil cu
red bands, then fairly flat going to the NIR
attributed to the leaf structure, variation in l
area.

The first derivative (FD) curve of the reflectance shows the variations and locations of the major valleys and highs of the reflectance curve. Derivative methods have been used in analytical spectroscopy for purposes stated by O'Haver (2001) which are: (a) spectral discrimination, as a qualitative fingerprinting technique to accentuate small structural differences between nearly identical spectra; (b) quantitative analysis, as a technique for the correction for irrelevant background absorption and as a way to facilitate multicomponent analysis. When values of the FD are plotted, it can be seen that peaks and troughs occur within or around the 970 nm wavelength. Peaks occur where FD crosses from positive (through zero) to negative. Troughs occur where FD crosses from negative to positive. The exact position of a peak or trough is where there is a largest change of the slope, in this case, rate of change of the spectrum with respect to the wavelength.

Water absorption – VWC versus the visible/NIR bands

The VWC derived from the 970 nm absorption wavelength is plotted against the visible (blue, 470nm; green, 550 nm; red, 680 nm) and NIR bands (820 nm) as shown in Figure 2. The influence of the vegetation water content on the visible bands affirms the results suggested by Li et al. (2001) that a decrease in visible reflectance and an increase in NIR reflectance would indicate higher water content in plants. Our results show, however, an insignificant direct relationship between VWC and NIR (r^2=0.07).

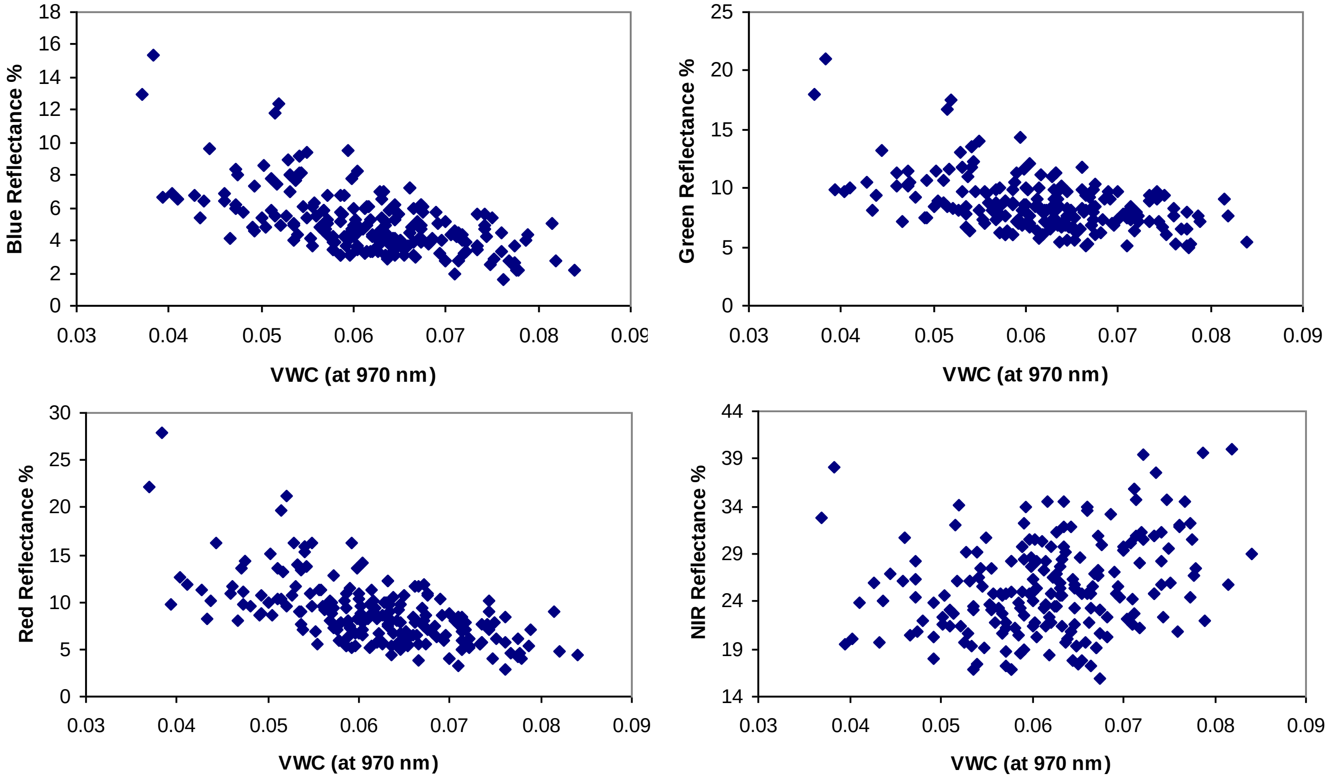


Figure 2: Scatter plots of VWC against the blue band (top left), green band (top right), red band (bottom left), and NIR (bottom right).

Water absorption – VWC versus the existing vegetation indices

The comparative strength of the correlations between VWC and the other existing vegetation indices can provide additional insights of the behavior of the absorption feature at 970 nm. We plotted VWC as a function of the VI and found that the most VI correlated significantly to the vegetation water content.

Although the plots suggest VIs may be good indicators of VWC, other authors such as Penuelas et al. (1997), discourage the use of indices that utilize the visible part of the spectrum. Reflectance between 400 nm and 710 nm are primarily affected by the chlorophyll content and the leaf internal structure (Ceccato et al., 2002). NDVI for instance measures green biomass of the vegetation and is affected by structural and color changes. Therefore, the effects observed may not be related to the changes of water concentration in plants alone but by some other contributory factors.

Figure 3 shows multiple plots illustrating the trends of the VWC when plotted against a number of existing vegetation indices within the visible and NIR spectral range. The matrix plot also shows the behaviors of each individual index against other indices. It is evident that most of the indices, WRDVI and CI specifically, saturate at higher VWC. The results may denote another limitation of these indices for VWC estimation.

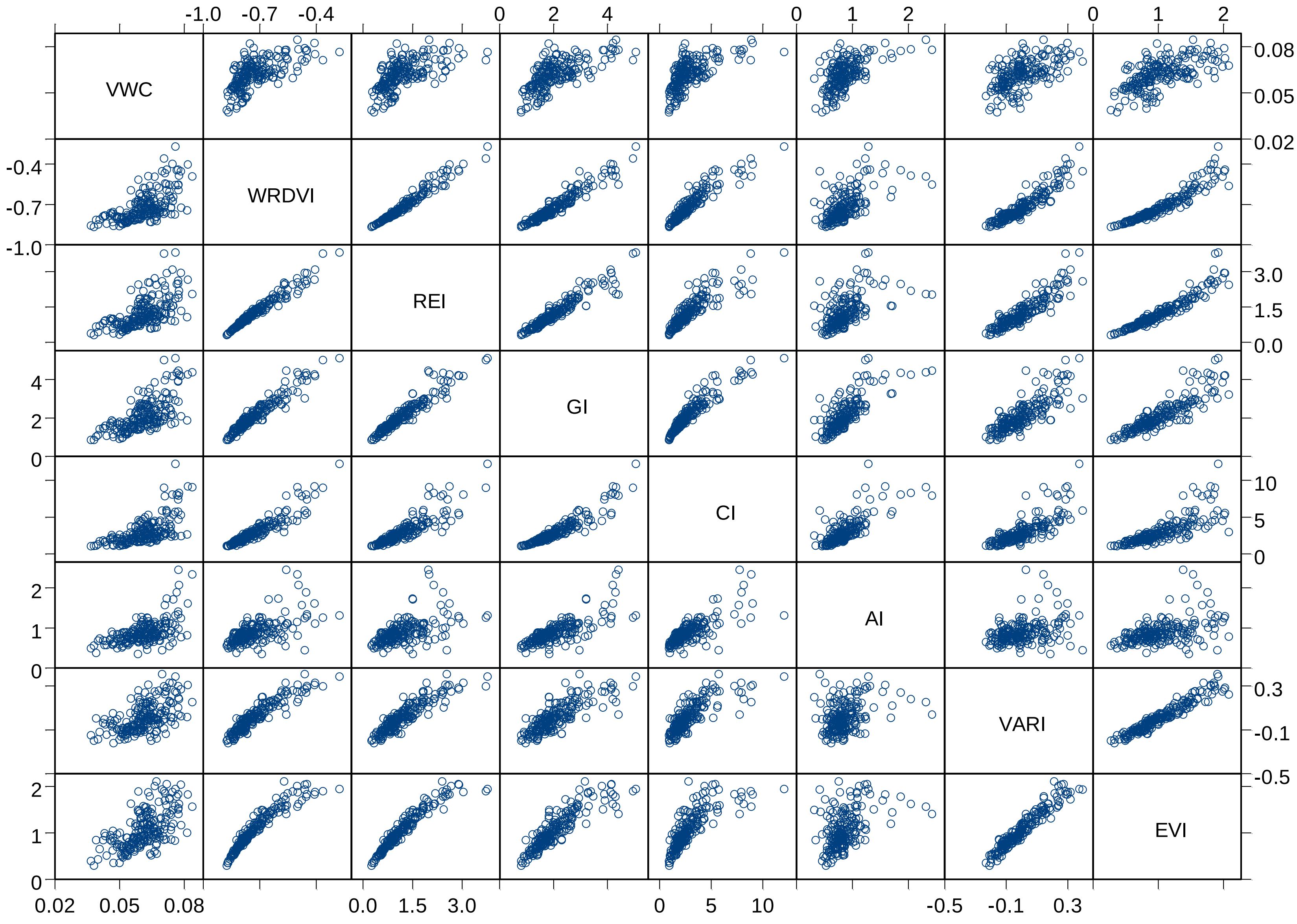


Figure 3: Scatter plot matrix of VWC against WRDVI, REI, GI, CI, AI, VARI and EVI.

Water absorption (VWC) versus Vegetation Water Content Indices

Two VWC indices were computed from the canopy reflectance data – the WBI and the revised NDWI. In addition, the performance of the NDVI was evaluated against the 970 nm absorption feature. Another ratio-based index, CVWI, was introduced to improve the VWC remote estimation.

Based on the R^2 values in the correlation plots (Figure 4) between VWC at 970 nm and the individual VWC indices including the NDVI, significant linear relationships were observed. NDVI explains a higher sensitivity when all spectral samples were taken into account (Table 1). The WBI and the NDWI reflect a similar trend of spectral clustering around the middle. This explains an almost perfect linearity between the two. R900 and R857 are both located on the NIR plateau that may simultaneously be influenced with the same amount of variation as the spectra change with differing VWC. The performance of each water index suggests that either of the two can be exploited to explain differences in vegetation water content. The NDWI, however, is better perceived as a good index, given that it employs spectral difference rather than just simple ratio like its WBI counterpart. Equation 4 can be modified to employ the 900 nm instead of the 857 nm as a reference wavelength to track the variation of leaf internal structure and dry matter content variations.

The CVWI displays the lowest correlation (R^2=0.43) among the indices evaluated. The first thing evident is that while the three indices summon for linearity, the CVWI disperses in pattern.

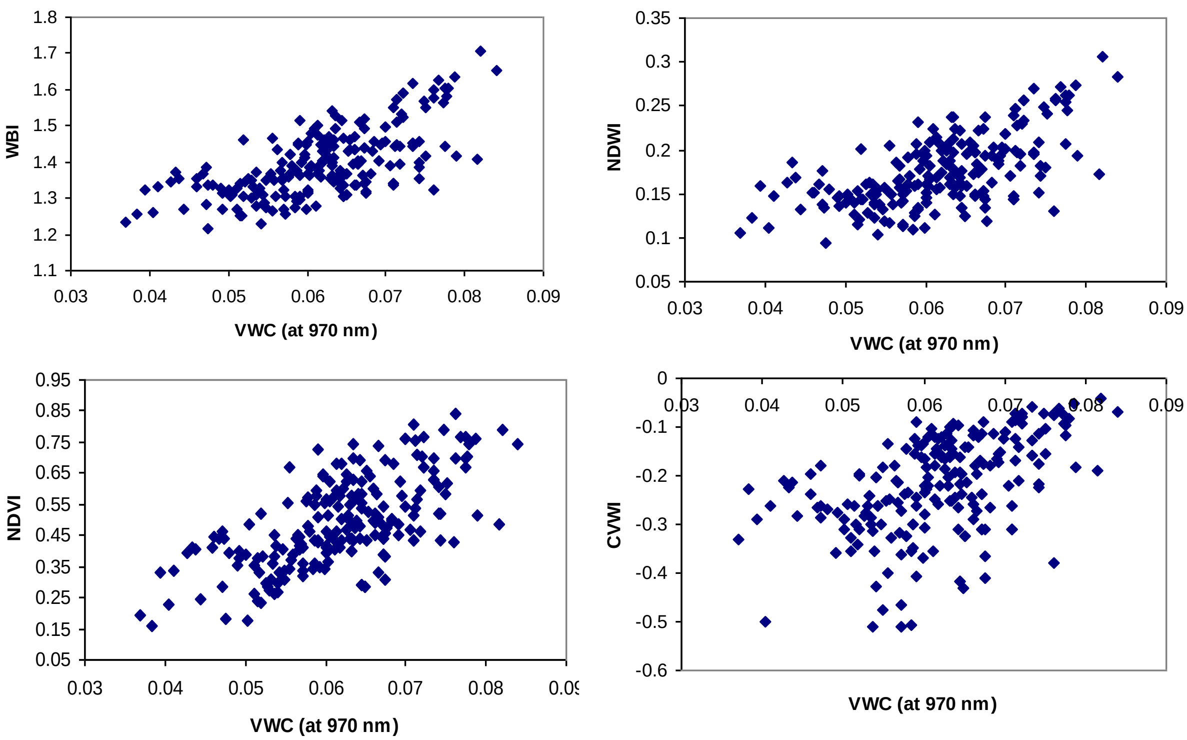


Figure 4: Scatter plots of VWC against the WBI (top left), NDWI (top right), NDVI (bottom left), and CVWI (bottom right).

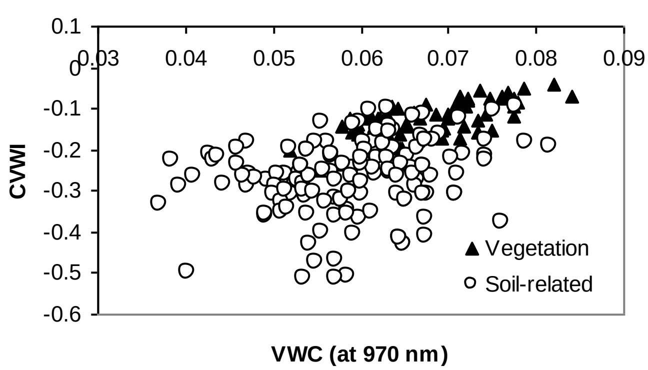
Table 1: Maximum R^2 values between VWC and the water content indices.

Vegetation Index	All Spectral Samples (R^2)	Vegetation Spectral Samples (R^2)
WBI	0.55	0.48
NDWI	0.55	0.46
NDVI	0.56	0.20
CVWI	0.43	0.49

The dispersion, however, denotes a hidden structure within the samples. Inspection of the spectral signatures reveals that a number of samples were soil-dominated based on the spectral behaviors observed in the visible and NIR bands. Table 1 shows the correlation R^2 when samples were further segregated to having pure vegetation only. Considerable decrease in relationships was noticeable for the WBI and NDWI against the VWC, 0.48 and 0.46, respectively. The differences were better explained in the way the indices behaved against the soil-dominated set of spectra. A sub-section for this is allocated in the subsequent discussion.

CVWI has posted an improved correlation coefficient. We found this unsurprising by any means as the main intent of the new index is to improve the estimation of VWC. With the concept of highlighting the absorption feature at 970 nm and emphasizing its importance in the index, the CVWI tended to differentiate the spectra from pure vegetation from that of soil-affected set. How this demarcation happened can be rationalized through looking at the equation itself.

Reflectance at the 970 nm is highly correlated with the 900 nm (R^2=0.90) for the vegetation spectral samples. This correspondence has led values of the CVWI of vegetative samples (first set) to be less than those from soil-affected samples (second set) as the denominator bent to become large. Minimum and maximum values of the first set were -0.252 and -0.052, respectively. The second set revealed a larger range with minimum and maximum values of -0.619 and -0.010, respectively. There was still an overlap among values (Figure 5). Nonetheless, put side by side with the resulting values from other indices, the CVWI could have the potential to differentiate the two sets.



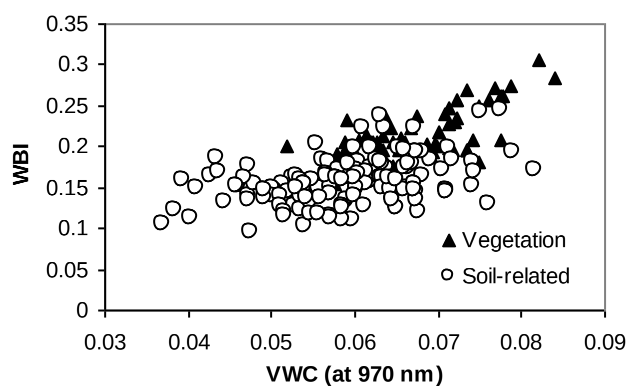


Figure 5: Scatter plots of VWC against the CVWI (left) and WBI (right) after samples were subdivided.

Table 2: Cross-validation of 'all samples' showing selected accuracy indicators. Significance at 0.01 alpha levels are enclosed in parenthesis.

Index	Pearson Correlation	R^2cv	RMSEcv	Shrinkage
WBI	0.57 (<0.01)	0.33	0.109	0.234
NDWI	0.54 (<0.01)	0.29	0.055	0.263
NDVI	0.58 (<0.01)	0.33	0.126	0.230
CVWI	0.46 (<0.01)	0.21	0.171	0.219

Cross-validation to test accuracy of the indices

The accuracy with which the VWC can be approximated from the identified vegetation water content indices was assessed using a cross-validation procedure. Results can be found in Tables 2 and 3.

The calibration procedure utilized another set of data that was purposely left out to cross-validate findings. A total of 73 samples were analyzed for the test. This step allowed us to spot how well the prediction equation from the original dataset fits the data from the test dataset. Whether or not we have increased our confidence that the sample prediction equation is a good estimate of the population prediction equation depends how good the prediction equation fits to both sets. The combination of cross-validated R^2 and RMSE (RMSEcv) were used as the accuracy indicators of the index in predicting the vegetation water content. To know how much R has shrunk when the beta weights were applied to a new sample, shrinkage statistics was put into operation. Generally, a shrinkage value of <0.05 could indicate that our findings in the regression procedure could be generalized.

Differences among the four indices are generally quite small. Using only the vegetative samples, Table 3 shows that although NDWI came out the least in RMSEcv = 0.011, it also exhibited the smallest cross-validated R^2 and a shrinkage of 0.126. WBI performed fairly the same as the NDWI. The CVWI shows the most significant relationship based on the results of the RMSEcv = 0.013 and a smaller shrinkage of 0.028. The Pearson correlation was fairly high as well.

It has been desired that the VWC index should be sensitive to, and could disintegrate the vegetation spectra from, the soil-related spectra. Table 2 looks at how the indices behaved when all samples are combined and then cross-validated against the test dataset. NDWI returned the least RMSEcv value, which denoted insensitivity to presence of soil spectra. The WBI and the CVWI appeared to be sensitive to soil-presence; changes of the RMSEcv values were huge.

Table 3: Cross-validation of 'first set' only showing selected accuracy indicators. Significance at 0.05* and 0.01** alpha levels are enclosed in parenthesis.

Index	Pearson Correlation	R^2cv	RMSEcv	Shrinkage
WBI	0.60 (0.023*)	0.36	0.018	0.122
NDWI	0.58 (0.029*)	0.34	0.011	0.126
NDVI	0.72 (0.004**)	0.52	0.021	0.312
CVWI	0.68 (0.007**)	0.46	0.013	0.028

Figure 6 illustrates the linearity of the computed water indices against the estimated values for the vegetative samples. No saturation tendencies were observed among the four tested VIs.

The results reported in this manuscript were calculated from a dataset collected using a field spectrometer. The use of the field hyperspectral dataset was perceived to facilitate the real behavior of the spectrally-derived vegetation water content. Having field conditions integrated into the spectrum enabled us to look into the separation of the vegetative samples from the soil-related ones. Despite our efforts to eliminate spectral noise in-situ, the sun illumination and sensor performance might still have effects to the amount of energy received by the leaves. Nonetheless, utmost care was employed to maintain the same sensor sampling height for all samples in all study plots. Further, each individual spectrum was checked upon plotting and before any analysis of the indices was made.

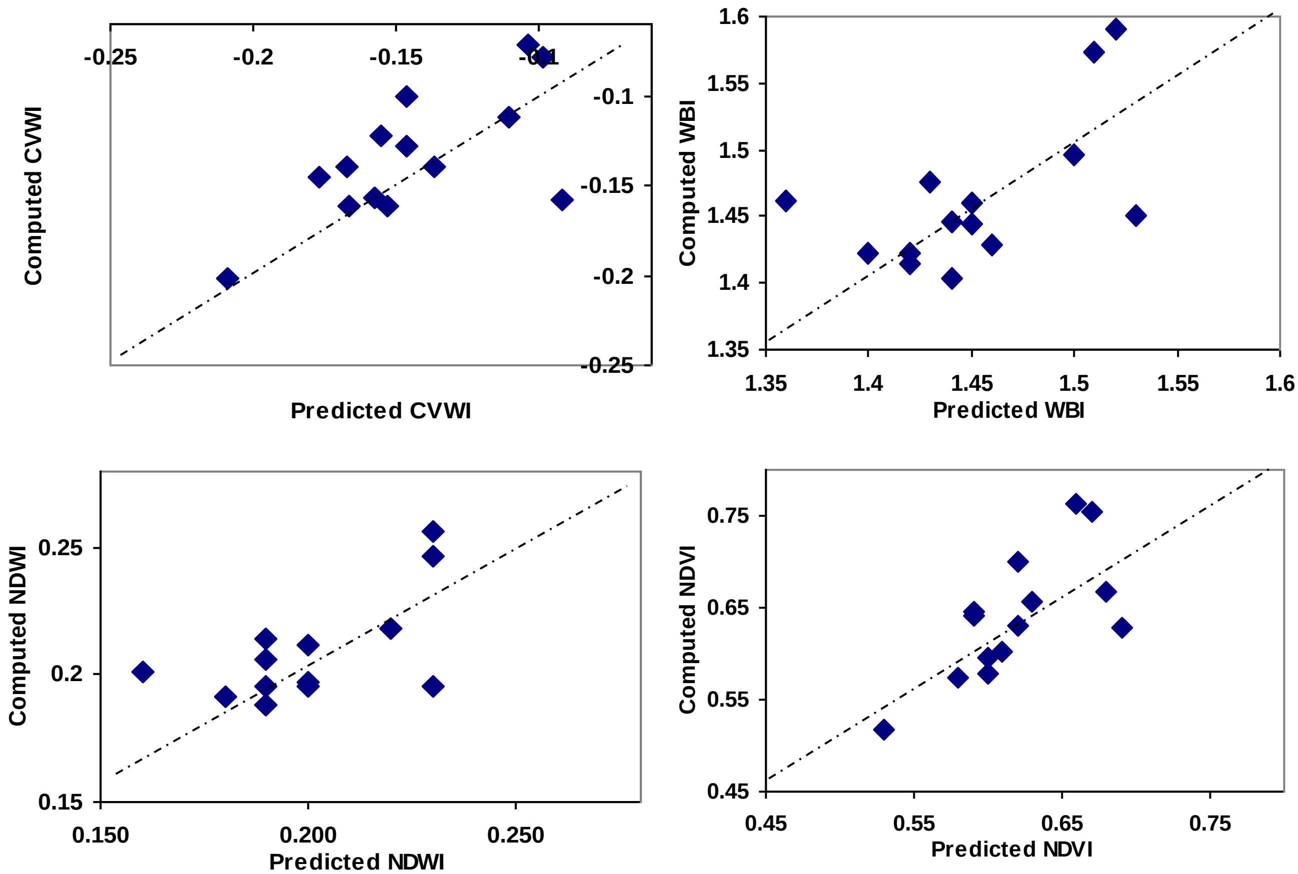


Figure 6: Cross-validated estimated or predicted water indices versus computed indices: CVWI (top left), WBI (top right), NDWI (bottom left) and NDVI (bottom right).

In future studies, the inclusion of specific vegetation species should affirm whether or not the vegetation water indices are species-dependent or the absorption feature is a variable of plant types. Similarly, other SWIR water wavelength depths should be looked into such as the 1200 nm and other suitable indices should be exploited that could further confirm the relationships between VWC at 970 nm and the hyperspectral-derived water content indices.

4. Conclusions

This paper aimed to assess how efficiently existing VWC indices that are applicable to the contiguous bands, link up to the amounts of water content obtained from the known 970 nm absorption channel. The downward deflection at 970 nm, to start with, initially declared as not pronounced compared to other water absorption bands, was seen as an interesting feature that quantified the vegetation water absorption depth.

Among the present VWC indices, the WBI appeared to be sensitive to the changes of the absorption depths, therefore, the vegetation water content. Additionally, this relationship confirmed previous results on WBI against ground-based VWC (Penuelas et al., 1997) and canopy WC (Serrano et al., 2000). The NDWI, even with the substitution of bands, from the original 1240 nm absorption channel to 970 nm, showed similar trends with the WBI in discriminating the water status of vegetation from the computed absorption depths. In the end, both indices presented comparable statistical results.

Combining the indices in order to highlight weak, yet significant, water absorption feature appeared to respond to the canopy water content well. CVWI showed a promise in assessing the vegetation water status derived from the 970 nm absorption characteristic of the spectra.

When soil sensitivity was introduced into the analysis, the NDWI failed to show any potential. Reasonable sensitivity values were observed in CVWI, even also with WBI. CVWI came out best in the cross-validation shrinkage statistics when the estimated and calculated values were compared.

In summary, our results reinforced the possibility of estimating VWC at the canopy level as suggested by previous reports. WBI and NDWI exhibited significant performance for VWC detection. However, soil influence may be a factor for them when effects due to soil are taken into consideration. CVWI offered a simple, easy, yet robust method of estimating VWC using hyperspectral field data. It also offers the possibility of its utility to hyperspectral images.

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