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Spectral absorption features as indicators of water status in coast live oak (*Quercus agrifolia*) leaves

R. PU*, S. GE, N. M. KELLY and P. GONG

Centre for Assessment & Monitoring of Forest & Environmental Resources (CAMFER), 145 Mulford Hall, University of California, Berkeley, CA 94720-3114, USA

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Abstract. A total of 139 reflectance spectra (between 350 and 2500 nm) from coast live oak (*Quercus agrifolia*) leaves were measured in the laboratory with a spectrometer FieldSpec®Pro FR. Correlation analysis was conducted between absorption features, three-band ratio indices derived from the spectra and corresponding relative water content (RWC, %) of oak leaves. The experimental results indicate that there exist linear relationships between the RWC of oak leaves and absorption feature parameters: wavelength position (WAVE), absorption feature depth (DEP), width (WID) and the multiplication of DEP and WID (AREA) at the 975 nm, 1200 nm and 1750 nm positions and two three-band ratio indices: $RATIO_{975}$ and $RATIO_{1200}$, derived at 975 nm and 1200 nm. AREA has a higher and more stable correlation with RWC compared to other features. It is worthy of noting that the two three-band ratio indices, $RATIO_{975}$ and $RATIO_{1200}$, may have potential application in assessing water status in vegetation.

1. Introduction

Recently, a large number of coast live oak (*Quercus agrifolia*), Tanoak (*Lithocarpus densiflorus*) and black oak (*Q. kelloggii*) trees have died in coastal areas of California, USA. This epidemic is characterized by a distinct set of symptoms (McPherson *et al.* 2000), and has been termed; 'Sudden Oak Death' (SOD). In addition to a suite of symptoms found on the trunks of infected trees, the foliage of infected trees appears to die rapidly, changing colour from dark green to reddish-brown within a few weeks. We suspect that the foliage of infected trees has a different water status from healthy leaves even when they appear green. This led us to examine the water status of infected oak leaves and to search for its spectral indicators. Relative water content (RWC) is one measure of plant water status and is widely used. RWC is usually calculated from weights of fresh leaves just collected in the field and weights of leaves after being completely dried in an oven. If used in large areas, this method is time consuming and labor intensive. Therefore, non-destructive and instantaneous methods are desirable for assessing the physiological water status of an entire forest area or a community in the field. Evaluating water status in vegetation is an important area in hyperspectral remote sensing (Goetz *et al.* 1985, Curran *et al.*

*email: rpu@nature.berkeley.edu

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1997). Previous work on assessing the plant water status mainly depends on spectral absorption features by water in the 400–2500 nm region. For examples, Peñuelas *et al.* (1993, 1996) studied the reflectances of gerbera, pepper, bean plants and wheat in the 950–970 nm region as an indicator of water status, and their results showed that the ratio of the reflectance at 970 nm, one of the water absorption bands, to the reflectance at 900 nm as the reference wavelength (R970/R900 or Water Index, WI) closely tracked the changes in RWC, leaf water potential, stomatal conductance, and cell wall elasticity. Tian *et al.* (2001) studied spectroscopic determination of wheat water status using spectral absorption features between 1650 and 1850 nm measured with a spectrometer and obtained a high prediction accuracy of wheat RWC (relative errors of predicted RWCs $<12\%$). According to Curran (1989), there exist several spectral absorption bands by water in vegetation in the 400–2500 nm region, whose central wavelengths are near 970 nm, 1200 nm, 1400 nm and 1940 nm. In addition, the reflectance of dry vegetation shows an absorption feature centred at 1780 nm by other chemicals (cellulose, sugar and starch (Curran 1989)) rather than by water because the pure water does not (Palmer and Williams 1974). In general, the reflectance spectra of green and yellow leaves in those absorption bands centred at 970 nm, 1200 nm, 1450 nm, 1900 nm and 1940 nm are quickly saturated and solely dominated (Elvidge 1990) by changes in leaf water content. For coast live oak leaves, based on our preliminary analysis in this study, the reflectances at bands 970 nm and 1200 nm are related to leaf RWC, varying from 10% to 60%.

Therefore, we designed an experiment to analyse the relationships between the change of liquid water content in the leaves of coast live oak and the changes of spectral absorption features, at wavelengths centred near 975 nm, 1200 nm, and 1750 nm, and three-band ratio indices derived from spectral regions centred at 975 nm and 1200 nm.

2. Field sampling and data measurement

2.1. *Field sampling*

A total of 139 coast live oak leaf samples were collected at two sites, China Camp State Park (122°29′50″W, 38°00′30″N)) and the campus of University of California at Berkeley (122°14′40″W, 37°52′40″N), on 6 October and 20 November 2000, respectively. In order to consider the effects of any high variability of water content in both healthy and infected leaves on sample spectra, samples of oak leaves were randomly collected from branches at different canopy surface positions from different trees. These samples included green fresh leaves, yellowish-brown senescent leaves and close dry grey leaves. Ninety-two samples were taken from 31 oak trees at different healthy levels: healthy (trees with no apparent SOD symptoms on the trunk), infected (trees with at least one of the symptoms of SOD) and newly dead (trees with reddish-brown foliage, and SOD symptoms on the trunk) at the China Camp State Park site, and 47 samples taken from four healthy trees on the Berkeley campus.

The leaf samples were collected in the field and were immediately sealed in plastic bags, then were sent to the CAMFER laboratory, UC Berkeley for spectral reflectance measurement with a FieldSpec®Pro FR (Analytical Spectral Devices, Inc., USA). After each leaf spectral measurement was taken, the leaves were weighed with an electronic scale immediately. They were then dried for second weighing.

2.2. *Reflectance spectra*

The FieldSpec®Pro FR, covering the spectral range between 350 nm and 2500 nm, consists of three separate spectrometers. The first spectrometer has a spectral resolution of 3 nm and the second and third have the same spectral resolution of approximately 10 nm. The whole spectral data are available for further processing by the controlling software. All spectra were measured at the nadir direction of the radiometer with a 25° FOV. Lighting is achieved with two 500 W halogen tungsten filament lamps. The distance between the spectroradiometer and the leaf samples was about 5 cm to allow within-leaf area radiance measurement. White reference current was measured every 5–10 minutes. Each leaf sample consisted of an overlapped piling of 5–10 leaves to eliminate the possible effect of background (black cloth) on the spectrum (based on our experiment, a spectrum of an overlapped piling of five oak leaves becomes stable). Each sample was repeatedly measured ten times with the spectrometer, five from adaxial surface and five from abaxial surface, so as to get an average spectral curve for each sample.

2.3. *Relative water content (RWC)*

Every oak leaf sample was immediately weighed after spectral measurement (Fresh Weight, FW). Then they were dried in an oven at 65°C until constant weight (Dry Weight, DW) was reached. Finally, the relative water content (RWC, %) was calculated using the formula: RWC = 100(FW − DW)/FW.

3. Method

Figure 1 shows three water absorption bands of oak leaves, which were used for extracting absorption feature parameters in this study. They are centred at 975 nm (920–1120 nm), 1200 nm (1070–1320 nm) and 1750 nm (1650–1850 nm). The third band is an indirect absorption band, namely absorbing spectrum through other chemicals such as cellulose (Curran 1989). For the first two absorption bands, we also calculated three-band ratio indices.

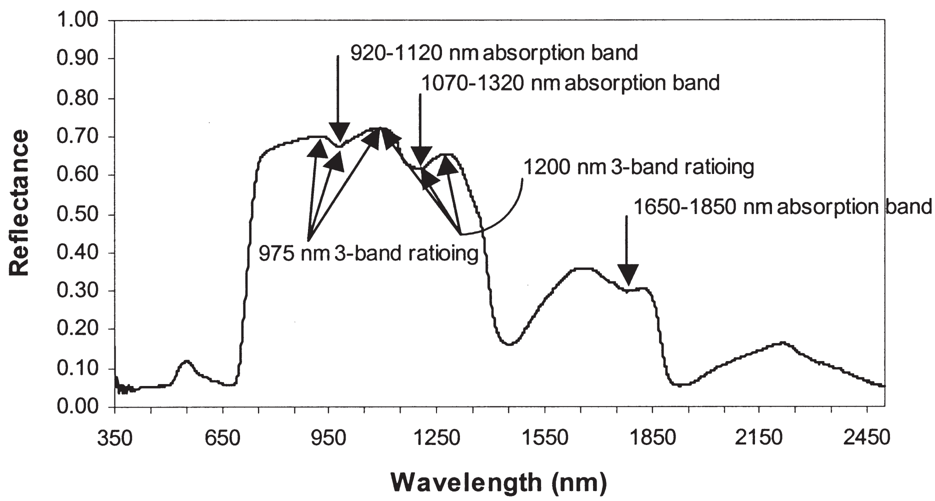


Figure 1. A typical reflectance spectrum of coast live oak, on which three-absorption band positions and two three-band ratioing positions are shown.

3.1. *Extraction of absorption features*

Absorption features in a reflectance spectrum are characterized in terms of their wavelength position (nm), depth, area, and asymmetry (relative value) with a continuum removal procedure (Schowengerdt 1997) (figure 2), somewhat different from a spectral normalizing technique. The continuum is defined manually as a piecewise-linear envelope enclosing the radiance spectra. In the procedure, the spectra of individual samples are each adjusted by dividing them by the continuum. The modified spectra exhibit a flat background because of this operation, but retain different absorption features. The flat background or the hull means no absorption feature appearance. Figure 2 used a part (850–1850 nm) of a typical spectrum of coast live leaves to illustrate the procedure operation. With the adjusted spectra by the continuum removal, it is easy to define the absorption features. The absorption position (WAVE) is defined as the wavelength position of minimum adjusted reflectance of an absorption feature. The absorption depth (DEP) is the depth of the feature minimum relative to the hull. The width of absorption (WID) is full wavelength width at half DEP (nm). The absorption area (AREA) is the area of the absorption feature that is the product of DEP and WID. The asymmetry of an absorption feature is derived as the ratio of the area left (Area A, the product of DEP and a) of the absorption centre to the area right (Area B, the product of DEP and b (WID − a)) of the absorption centre (figure 2).

The 139 spectra of oak leaf samples were processed using the continuum removal technique. All absorption features at 975, 1200 and 1750 nm were calculated according to the definitions made above and figure 2.

3.2. *Three-band ratio indices*

According to the three-channel ratio technique by Gao *et al.* (1993) and the thought of three-band ratio by Feind and Welch (1995), we defined two three-band ratio indices for the absorption bands centred at 975 nm and 1200 nm as:

$$\mathrm{RATIO}_{975} = 2R_{960\text{–}990}/(R_{920\text{–}940} + R_{1090\text{–}1110}) \quad (1)$$

$$\mathrm{RATIO}_{1200} = 2R_{1180-1220}/(R_{1090-1110} + R_{1265-1285}) \quad (2)$$

where, RATIO_{975} and RATIO_{1200} are three-band ratio indices at 975 and 1200 nm, respectively. $R_{960\text{–}990}$ denotes an average spectral reflectance in the 960–990 nm region. Other average reflectances in both (1) and (2) have the same definition. The positions of the two three-band ratio indices can also be seen in figure 1. Since the varying range of the RATIO_{1750} is too small to correlate with change of RWC, We did not test the correlation of the ratio with RWC in this study.

Gao *et al.* (1993) applied the three-band ratio technique to effectively remove the linear surface reflectance effect and give a mean observed transmittance for the 0.94 μm and 1.14 μm water vapour bands from AVIRIS (Airborne Visible/Infrared Imaging Spectrometer) images. Gao *et al.* (1993) defined a three-band ratio similar to ours but with different absorption centres while Feind and Welch (1995) defined a three-band ratio using average radiance measurement of two water vapour absorption bands (0.94 μm and 1.13 μm) divided by the water vapour window band (1.04 μm) to extract cloud fraction mask from AVIRIS data.

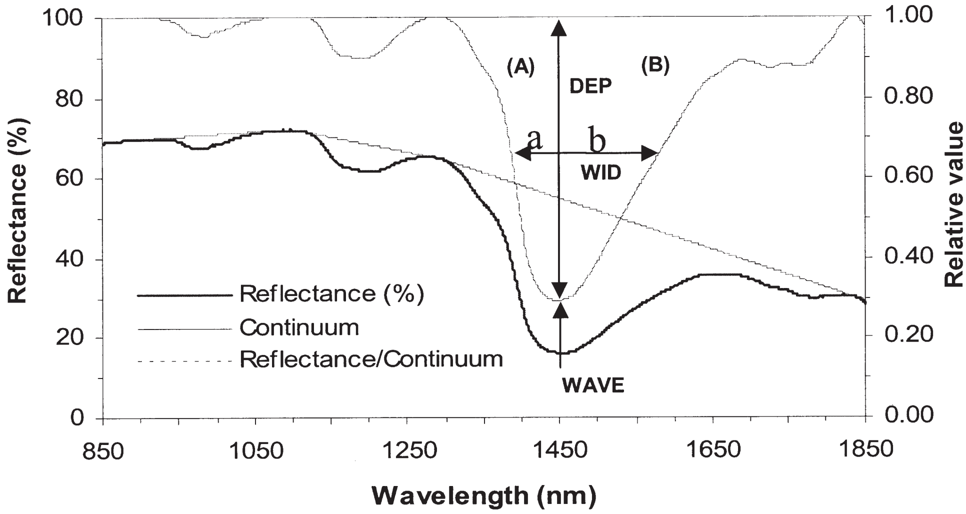


Figure 2. A part of the coast live oak leaf spectrum adjusted by a continuum removal technique (Schowengerdt, 1997) and the definitions of three absorption features (for abbreviations, see text).

3.2. *Correlation analysis*

In this study, the correlation analysis was conducted between six spectral parameters: four absorption features, WAVE, DEP, WID and AREA, and two three-band ratio indices, $RATIO_{975}$ and $RATIO_{1200}$, and RWC of oak leaves.

4. Results and analysis

4.1. *Spectral characteristics of coast live oak leaves*

Figure 3 shows several reflectance spectra of oak leaves measured in this experiment. These spectral curves were randomly selected from spectral samples based on

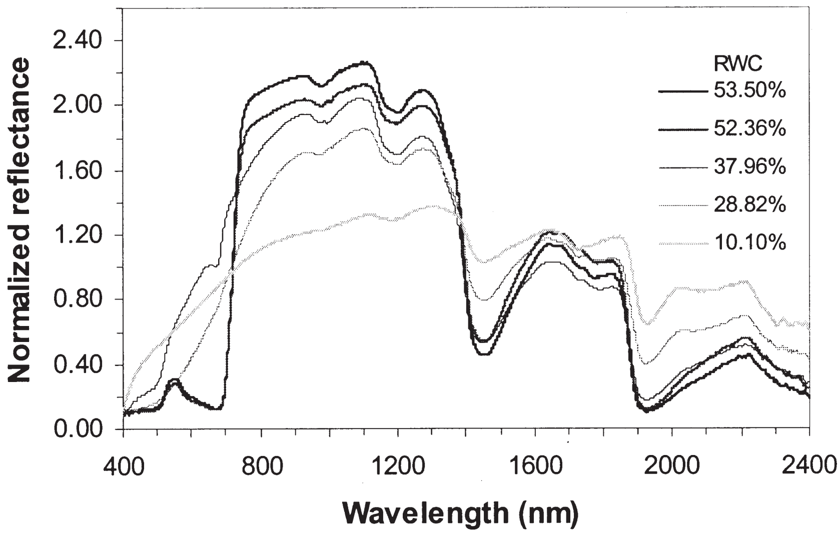


Figure 3. Spectral absorption features of coast live oak leaves at three absorption bands centred near 975 nm, 1200 nm and 1750 nm, respectively.

RWC values normalized in order to reduce the effect of the change of light condition on reflectance measurement. The reflectance differences between different RWCs of leaf samples are considerably large in the 920–1120 nm, 1070–1320 nm, and 1650–1850 nm regions. Prominent liquid water absorption features centred near 970 nm, 1200 nm, 1450 nm, and 1940 nm are obvious (figure 3). The absorption features at 975 nm and 1200 nm become apparent as RWC increases. The reflectance in the 1650–1850 nm absorption band increases as the leaf RWC decreases. Moreover, the local trough curve in the 1650–1850 nm band seems to vary as the RWC changes. The calculated results of the spectral absorption depths, positions, areas verified these changes in spectral pattern in the vicinity of 975 nm, 1200 nm and 1750 nm. As leaf water content increases, the depth and area of the absorption features decrease at 1750 nm and increase at both 975 nm and 1200 nm; the absorption position (WAVE) is shifted to a longer wavelength at 1750 nm and to shorter wavelengths at 975 nm and 1200 nm. All results indicate that water has a dominant influence on the reflectance in the three absorption bands. Therefore, it is expected that the spectral absorption features at the three bands can be used to evaluate the water status of coast live oak leaves.

4.1. *Correlations between RWC and absorption features and three-band ratio indices*

Using the method described earlier, we extracted four absorption features: WAVE, DEP, WID, and AREA from the three absorption bands and two ratio indices: $RATIO_{975}$ and $RATIO_{1200}$ from the two bands of 975 nm and 1200 nm for each spectral sample. The absorption features and ratio indices derived from all 139 spectra were then correlated with corresponding RWC. The correlation analysis results were listed in table 1. From the table, it is apparent that every correlation coefficient between absorption features or ratio indices and RWC is significant at 0.99 confidence level even though those with WID at 975 nm, WAVE at 1200 nm and DEP at 1750 nm have a lower correlation coefficient. The results demonstrate

Table 1. Correlation analysis results between absorption features, three-band ratio indices (Y) and relative water content (RWC, %) (X). N = 139.

Absorption band	Feature	Slope (a)	Intercept (b)	Correlation coefficient
	WAVE	−0.5802	1014.3738	−0.6272
975 nm	DEP	0.0011	0.0008	0.8373
(920–1120 nm)	WID	0.3736	49.1011	0.4159
	AREA	0.0748	−0.1118	0.8114
	WAVE	−0.1606	1193.9095	−0.2872
1200 nm	DEP	0.0018	0.0219	0.8595
(1070–1320 nm)	WID	0.2547	75.9186	0.7751
	AREA	0.1676	1.5428	0.8611
	WAVE	1.3682	1714.3730	0.9273
1750 nm	DEP	−0.0002	0.0725	−0.3910
(1650–1850 nm)	WID	−0.7010	104.4959	−0.6663
	AREA	−0.0636	7.4466	−0.6810
975 nm	$RATIO_{975}$	−0.0009	0.9935	−0.8473
1200 nm	$RATIO_{1200}$	−0.0020	0.9851	−0.8603

that all the absorption features and ratio indices are indeed correlated with the RWC of coast live oak leaves.

Among these, the higher and more stable correlations are AREA and two ratio indices, especially derived from the 975 nm and 1200 nm bands. From the correlation results, it seems that absorption features and ratio indices derived from the bands 975 nm and 1200 nm are more useful than those from the 1750 nm band for evaluating water status of coast live oak leaves. This is because there do exist two prominent water absorption bands in vegetation, centred at 970 nm and 1200 nm, and caused by O-H chemical bond bend and the first overtone (Curran 1989). Figure 4 presents scatter plots of the absorption features and ratio indices and their corresponding RWCs except those with WID. From these scatter plots, it is easy to see that data points form two clusters, one located at the higher RWC end (40–60%, typically corresponding to fresh green leaves) and the other at the lower RWC end (<20%, typically corresponding to brown-grey leaves) and a few of them in between (corresponding to green-yellowish-brown leaves). This reflects the lack of oak leaf samples corresponding to green-yellowish-brown colour in the fields. After taking a closer look at these plots, we can see that better relationships indeed exist between RWC and absorption features. In this experiment, RWC varies from 0.45% to 57.94%. When RWC ranges from 40–60% (typical RWC of green leaves), the three absorption features and two ratio indices deviated largely from the regression line, and appeared to have poorer correlation with RWC. WAVE scatters the most from the regression line, especially for the 975 nm and 1200 nm bands. From the distribution tendency of data points on these plots, we can also conclude that AREA and two ratio indices can produce a higher correlation with RWC. Absorption bands 975 nm and 1200 nm are more effective than 1750 nm. Because they only require three bands, the two ratio indices have the potential for use in developing inexpensive instruments for leaf water status measurements.

5. Conclusions and remarks

Our experimental results indicate that there exist linear relationships between RWC of coast live oak leaves and absorption feature parameters: WAVE, DEP, WID and AREA derived from spectral bands around 975 nm, 1200 nm and 1750 nm. RWC is also highly correlated with two three-band ratio indices: $RATIO_{975}$ and $RATIO_{1200}$ derived from the 975 nm and 1200 nm bands. These prove that reflectance spectra of oak leaves in the 920–1120 nm and 1070–1320 nm regions are indeed dominated by their liquid water content, and the reflectance spectrum in the 1650–1850 nm region is also affected by its water content. As RWC of coast live oak leaves increase, the spectral absorption features gradually become obvious at the 975 nm and 1200 nm bands but disappear at the 1750 nm band. AREA has a higher and more stable correlation with RWC compared to other features for evaluating water status of oak leaves. The two three-band ratio indices, derived from the 975 nm and 1200 nm absorption bands, have potential application in assessing water status of vegetation.

In this experiment, the distribution of RWC data is not totally desirable due to the lack of samples with an RWC in the range of 20–40%. However, our preliminary conclusions agree well with those by Tian *et al.* (2001) for winter wheat leaves at the 1750 nm absorption band, with those by Peñuelas *et al.* (1993, 1996) for gerbera, pepper, and bean plant at the 970 nm absorption band, and those by Curran and Kupiec (1995) who used AVIRIS hyperspectral data in an analysis of slash pine

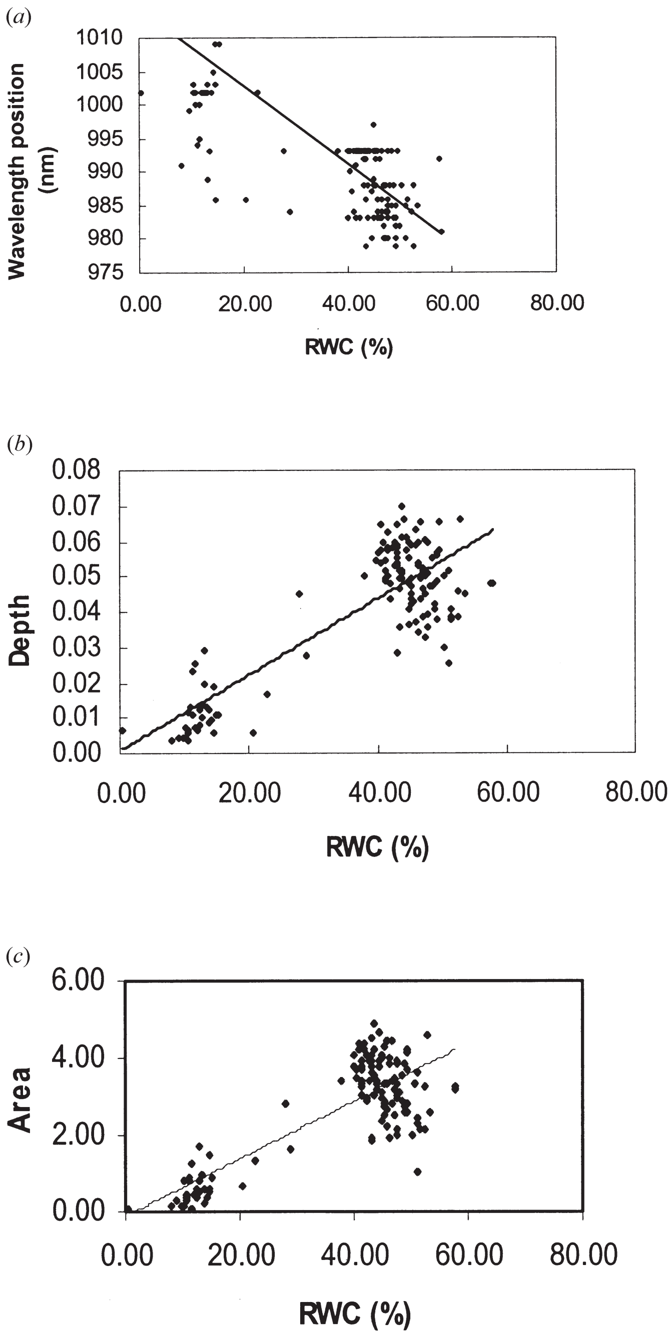
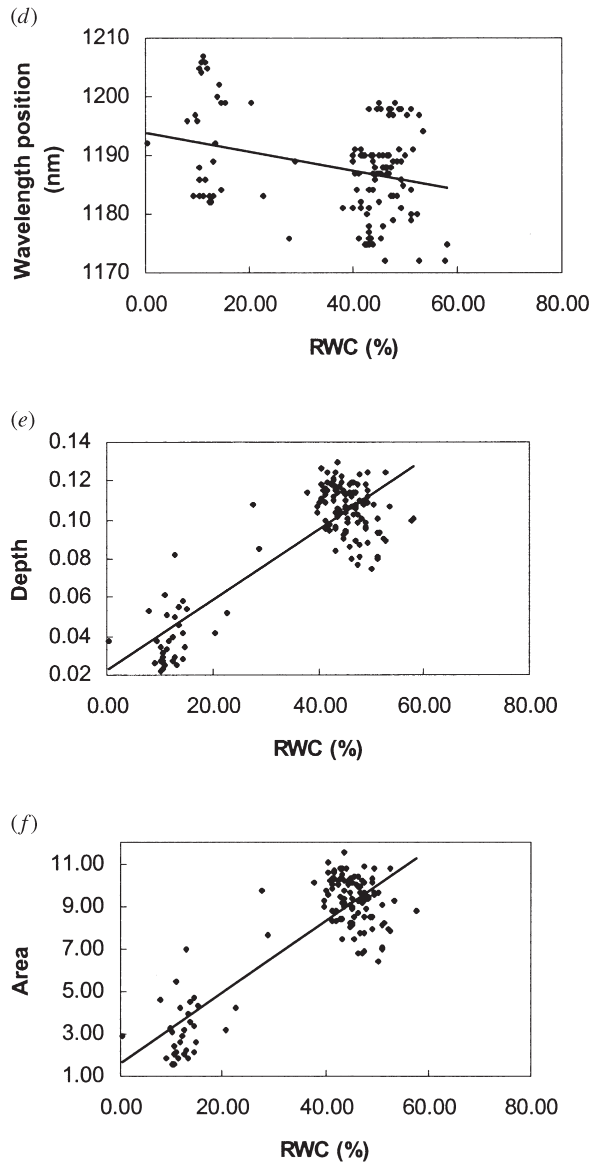
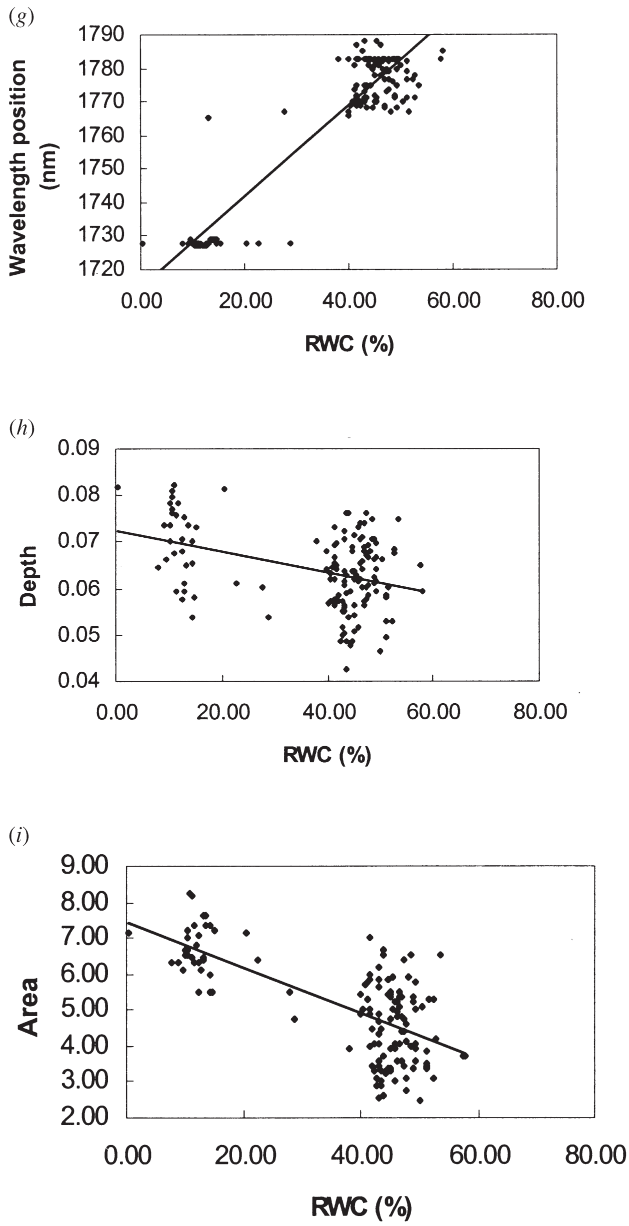


Figure 4. Scatter plots of absorption features with RWC (%). (*a–c*). WAVE, DEP and AREA with RWC at 975 nm; (*d–f*). WAVE, DEP and AREA with RWC at 1200 nm; (*g–i*). WAVE, DEP and AREA with RWC at 1750 nm; (*j*, *k*). Three-band ratio indices with RWC at (*j*) 975 nm and (*k*) 1200 nm. N = 139.



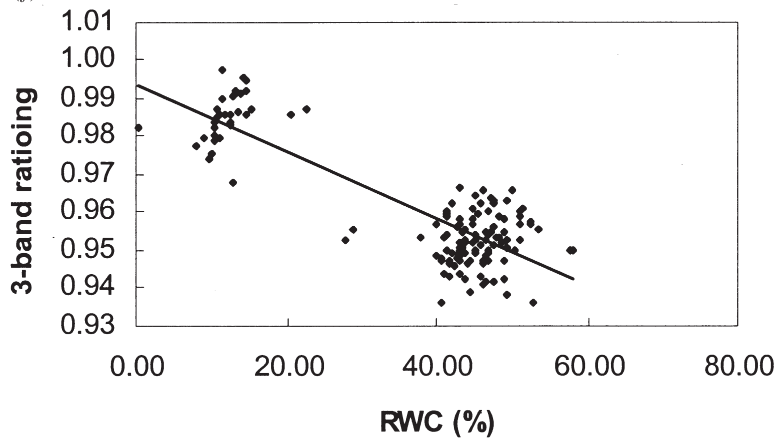
needles using all three absorption bands: 975 nm, 1200 nm and 1750 nm, in a multivariate regression model. This indicates that the spectral indicators used in this experiment are useful to assess water status of vegetation. The reflectance spectra of green vegetation in the 1.0–2.5 μm region are controlled by both the dominant liquid water and the dry compounds, such as lignin and cellulose (Gao and Goetz 1994). With a decrease in leaf water content, the dry materials account for a greater proportion of the leaf spectral feature (Elvidge 1990) (e.g. the spectral feature of dry leaf components at 1650–1850 nm is generally apparent). Study on spectral absorption features as indicators of water status is therefore very important to either



assessing vegetation water status or extracting other biochemical parameters such as lignin and cellulose.

Initially, we proposed to test if we can distinguish between infected and healthy trees using hyperspectral data. Since infected oak trees are suspected to fall in short of water inception, in this study we focused on the assessment of water status in relation to measured leaf spectral properties. Additional work is necessary to search for spectral differences that can serve as indicators of oak tree infection.

(j)



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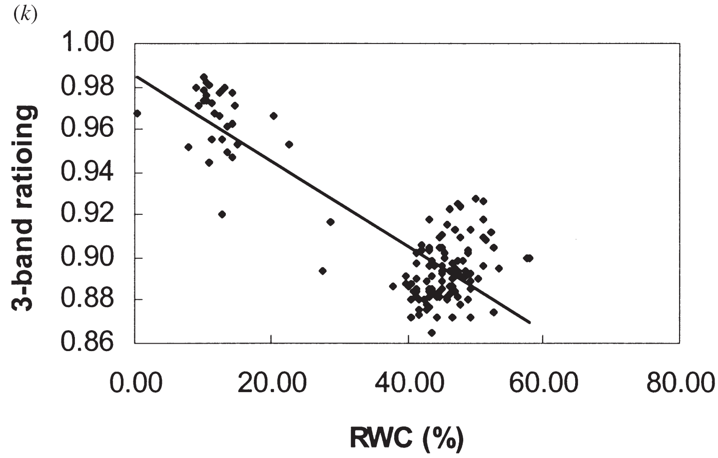

Figure 4. Continued.

Acknowledgments

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References

Curran, P. J., 1989, Remote sending of foliar chemistry. *Remote Sensing of Environment,* **30**, 271–278.

Curran, P. J., and Kupice, J. A., 1995, Imaging spectrometry: A new tool for ecology. In *Advances in Environmental Remote Sensing*, edited by F. M. Danson and S. E. Plummer, (Chichester: Wiley & Sons), pp. 71–88.

Curran, P. J., Kupice, J. A., and Smith, G. M., 1997, Remote sensing the biochemical composition of a slash pine canopy. *IEEE Transactions on Geoscience and Remote Sensing*, **35**, 415–420.

Elvidge, C. D., 1990, Visible and near infrared reflectance characteristics of dry plant materials. *International Journal of Remote Sensing*, **11**, 1775–1795.

Feind, R. E., and Welch, R. M., 1995, Cloud fraction and cloud shadow property retrievals from coregistered TIMS and AVIRIS imagery: the use of cloud morphology for registration. *IEEE Transactions on Geoscience and Remote Sensing*, **33**, 172–184.

Gao, B-C., Heidebrecht, K. B., and Goetz, A. F. H., 1993, Derivation of scaled surface reflectances from AVIRIS data. *Remote Sensing of Environment*, **44**, 165–178.

Gao, B-C., and Goetz, A. F. H., 1994, Extraction of dry leaf spectral features from reflectance spectra of green vegetation. *Remote Sensing of Environment*, **47**, 369–374.

Goetz, A. F. H., Vane, G., Solomon, J. E., and Rock, B. N., 1985, Imaging spectrometry for earth remote sensing. *Science*, **228**, 1147–1153.

McPherson, B. A., Wood, D. L., Storer, A. J., Svihra, P., Rizzo, D. M., Kelly, N. M., and Standiford, R. B., 2000, Oak mortality syndrome: sudden death of oaks and tanoaks. *Tree Notes*, No.26, 1–6.

Palmer, K. F., and Williams, D., 1974, Optical properties of water in the near infrared. *Journal of the Optical Society of America*, **64**, 1107–1110.

Peñuelas, J., Filella, I., Biel, C., Sweeano, L., and Save, R., 1993, The reflectance at the 950–970 nm region as an indicator of plant water status. *International Journal of Remote Sensing*, **14**, 1887–1905.

Peñuelas, J., Filella, I., and Sweeano, L., 1996, Cell wall elastivity and water index (R970nm/R900nm) in wheat under different nitrogen availabilities. *International Journal of Remote Sensing*, **17**, 373–382.

Schowengerdt, R. A., 1997, *Remote Sensing—Models and Methods for Image Processing* (London: Academic Press), pp.287–356.

Tian, Q., Tong, Q., Pu, R., Guo, X., and Zhao, C., 2001, Spectroscopic determination of wheat water status using 1650–1850 nm spectral absorption features. *International Journal of Remote Sensing*, **22**, 2329–2338.