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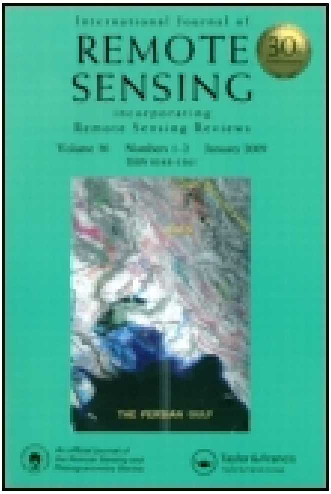

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Spectroscopic determination of wheat water status using 1650–1850 nm spectral absorption features

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Abstract. Wheat leaves were measured radiometrically in order to spectrally characterize the water deficiency symptoms. In this study, a FieldSpec-FR was used for measuring wheat leaf spectra. After the spectral analysis using a spectral normalizing technique, the spectral absorption feature parameters: wavelength position (nm), depth and area (relative value) were extracted from each wheat leaf spectrum. The relative water content (RWC) was measured for each wheat leaf sample. A linear regression analysis was conducted between the spectral absorption feature parameters and corresponding RWCs. The experimental results from 110 samples indicated that reflectance spectra of wheat leaves in the 1650–1850 nm region were dominated by water content. With a decrease in wheat leaf RWC, the 1650–1850 nm spectral absorption features gradually become obvious. The relative errors of predicted RWCs and the absolute error of predicted wavelength positions were calculated from 12 validation samples by established regression equations. The relative errors of predicted RWCs and the absolute error of predicted wavelength position (nm) were both low ($<6\%$ for RWCs by the depth and area and <12 nm for the wavelength position, respectively). Furthermore, we discuss the potential and limitations of spectroscopic determination of wheat RWC by using remote sensing technology.

1. Introduction

Most of North China is in a condition of water deficit. Deficiencies of water in agricultural lands result in a significant decrease in crop yield and loss of land productivity. The available measurements of crop water requirements are based on meteorology, soil water content, and plant parameters. Plant water status is usually expressed as relative water content (RWC), water potential, components of water potential (turgor pressure and osmotic potential) or transpiration and photosynthetic

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rates (Pearcy *et al.* 1989). They involve point measurements that are complicated, time consuming and difficult to integrate. Besides, such measurements on a large number of individual leaves are not only labor intensive but also subject to errors (Meyer *et al.* 1985). Extrapolation to whole plant and canopy is also a problem. Thus studies of plant water relations have been limited to relatively small spatial scales (Jarvis and McNaughton 1985). Non-destructive and instantaneous methods are desirable for assessing the physiological water status of an entire crop or community in the field.

The application of remote sensing techniques to study and/or evaluate water status in vegetation is an important aspect (Jackson and Ezra 1985, Jackson 1986). Sensing the thermal radiation emitted by the canopy is a way of assessing water stress (Penuelas *et al.* 1992, Nobel 1983, Berliner *et al.* 1984). CWSI (Crop Water Stress Index) (Jackson 1982) is one of the most widely used indices because it incorporates meteorological parameters. Another way of assessing the plant water status depends on spectral absorption features by water in the 400–2500 nm region. The potential of using leaf and crop reflectance for measuring water stress has been explored by several researchers. Bowman (1989) reported the potential of measuring plant water stress by using leaf reflectance. Penuelas *et al.* (1992, 1993, 1994, 1996) studied the reflectance in the 950–970 nm region as an indictor of water status, and the result showed that the ratio of the reflectance at 970 nm, one of the water absorption bands, to the reflectance at 900 nm as reference wavelength (R970/R900 or Water Index, WI) closely tracked the changes in relative water content (RWC), leaf water potential, stomatal conductance, and cell wall elasticity.

Reflectance spectra of green vegetation beyond 1300 nm are strongly influenced by liquid water absorption (Allen and Richardson 1968) also. Liquid water is a major component of fresh, green leaves. It can account for 40–80% of the fresh weight. Other compounds, such as cellulose and lignin, have very different absorption characteristics from that of liquid water (Elvidge 1990). These also contribute to the absorption signatures in reflectance spectra of fresh, green leaves. In particular, the reflectance of dry vegetation shows an absorption feature centered at 1720 nm, while the pure water (Palmer and Willianms 1974) does not. Gao and Goetz (1994) have particularly emphasized the effects of both leaf water and leaf biochemical constituents on short-wave reflectance. Raymond and Roger (1999) showed a spectral change in dry leaves with increasing amounts of water using Hapke's radiative transfer model (Hapke 1981, 1993), and noted that the apparent band minimum at 1730 nm shifts to longer wavelengths with increasing water, and absorption features become unclear. Although the positions of prominent liquid water absorptions are centered at 760 nm, 970 nm, 1190 nm, 1450 nm, 1900 nm and 1940 nm, the reflectances in these bands are quickly saturated and solely caused by changes in leaf water content (Elvidge 1990). However, the reflectance absorptions in the 1650–1850 nm region reflect not only the leaf water content, but also the contents of leaf cellulose and lignin, and are directly related to the plant growing status (Curran 1989, Zagolski 1996). Moreover, the 1650–1850 nm band combines an excellent soil-green vegetation spectral contrast with within band sensitivity to the leaf water content and the influence of the atmosphere on solar irradiance is small (Gausman 1978, Valley 1965).

In this study, a laboratory experiment was designed to further study the relationship between the change of 1650–1850 nm spectral absorption features of crop leaves and the change of liquid water content. Reflectance spectra of 110 wheat leaf samples and their RWC were measured. With a spectral normalizing technique (Green and

Graig 1985), we established the relationship between the 1650–1850 nm spectral absorption features and wheat RWC. In addition, we explored the potential to quantitatively detect the status of wheat water deficiencies by using remote sensing technology.

2. Materials and method

2.1. *Field sampling*

A total of 110 winter wheat leaf samples were collected from an experimental field before the wheat heading period in early May of 1999 in the outskirts of Beijing. In order to consider the effects of any high variability of water content on sample spectra and the future monitoring section of wheat by remote sensing sensors, samples of wheat leaves were systematically collected at different canopy positions from top to bottom randomly. These samples included green fresh leaves and brown senescent leaves which were all living on the wheat stems.

The leaf samples were collected in the field and were immediately sealed in plastic bags, then were sent to a laboratory nearby for spectral reflectance measurement with a FieldSpec-FR (Analytical Spectral Devices, Inc., USA). After one leaf spectral measurement was taken, the leaf was weighed with an electronic balance immediately. It took approximately 20–30 minutes from collecting leaf samples to measuring their spectra, while it took only 20–30 seconds between spectral measurement and leaf water weighing. Therefore, we can assume that the leaf water content did not significantly change from spectral measurement to leaf water weighing.

2.2. *Spectral reflectance measurements*

The spectral range covered by the FieldSpec-FR is from 350 nm to 2500 nm with three separate spectrometers coupled in a unique way. The first spectrometer measures the wavelength region from 350 nm to 1000 nm with a spectral resolution (FWHM, full-width-half-maximum) of approximately 3 nm; the second spectrometer and third cover 900 nm to 1850 nm and 1700 nm to 2500 nm, respectively, with the same spectral resolution (FWHM) of approximately 10 nm. The whole spectral data are available for further processing by the controlling software. All spectral measurements were made in a nadir orientation of the radiometer with 5° FOV under the two 500 W bromine-tungsten lamps. The distance between the spectroradiometer and the leaf samples was about 10 cm to allow radiance measurement of about 1 cm diameter area of the leaves. White reference current was measured before each leaf spectral sample was taken. Every sample was repeatedly measured 4 times, so as to get its average spectral curve.

2.3. *Relative water content (RWC)*

Every wheat leaf sample was immediately weighed after spectral measurement (Fresh Weight, FW). Then they were dried in an oven at 60°C until constant weight (Dry Weight, DW) was reached. Finally, the relative water content (RWC) was calculated according to the following formula:

$$\mathrm{RWC} = (\mathrm{FW} - \mathrm{DW})/\mathrm{FW} \tag{1}$$

2.4. *Characteristics of 1650–1850 nm absorption features*

Absorption features in reflectance spectra are characterized in terms of their wavelength position (μm), depth, area, and asymmetry (relative value) with a spectral normalizing technique (Clark and Roush 1984, Green and Graig 1985) (figure 1). The absorption position (WAV) is defined as the wavelength position of minimum 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 the FWHM whose unit is micrometer (μm). The absorption area (AREA) is the area of the absorption feature which is the product of DEP and WID. The upper convex hull is an envelope curve fitted over the original reflectance spectrum, having no absorption features. The absorption spectrum known as hull quotient is given by taking the ratio of the spectrum to the enveloping curve. The result is a re-scaling of the reflectance spectra to 100 percent if no absorption features occur. The asymmetry (ASY) of an absorption feature is derived as the ratio of the area left (Area A) of the absorption center to the area right (Area B) of the absorption center (figure 1).

The 110 spectra of wheat leaf samples were further processed using the spectral normalizing technique. All of the absorption features at 1650–1850 nm were calculated according to definitions by Green and Graig (1985) and figure 1.

3. Results and analysis

3.1. *Spectra of materials*

The reflectance spectra of leaves in this experiment show that reflectance in the 400–2500 nm region increases with decreasing leaf RWC and the reflectance difference between different RWCs of leaf samples is evident. Prominent liquid water absorption features centered near 970 nm, 1190 nm, 1450 nm, and 1940 nm are clear (figure 2). Of these, the major absorption features by the liquid water occur at wavelengths centered at 1450 nm and 1940 nm, respectively, as reported by most researchers. The spectral signatures of the other chemical components (e.g. lignin, cellulose, starch, protein, nitrogen) of green leaves are, to a large degree, masked by the water absorption features (Matson *et al.* 1994), because the water which comprises so much of the leaf is highly absorbing in the short-wave infrared.

3.2. *Spectral absorption features at 1650–1850 nm*

As can be seen from the spectra in figure 2, the spectral reflectances of absorption features at 1650–1850 nm increase with decrease of the leaf RWC. The spectral curves of leaf absorption spectrum also change in shape with varying RWC. In addition, the local trough curve at 1650–1850 nm seems to vary as the RWC change. The

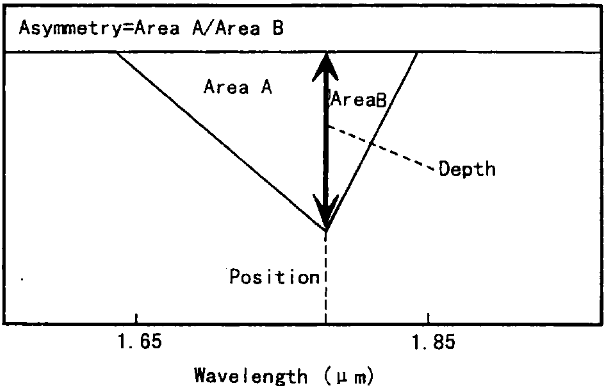

Figure 1. Definitions of absorption features.

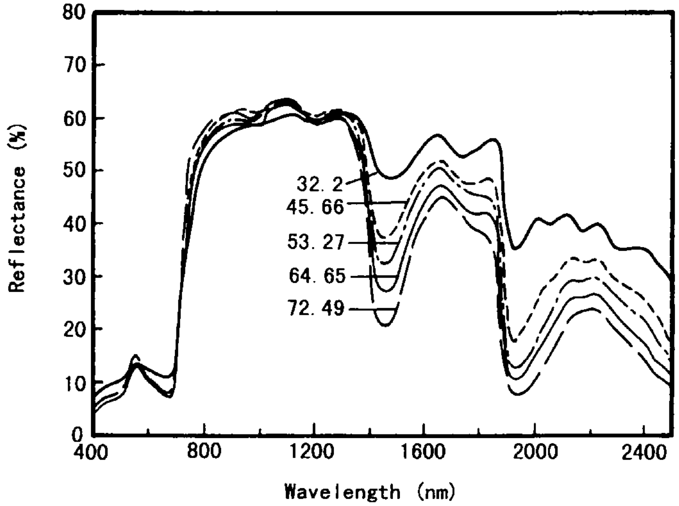

Figure 2. Spectral reflectances of wheat leaves at 1650–1850 nm with different RWCs, showing the absorption features of each spectrum and the numbers presented on each spectral curve to show corresponding RWCs.

calculated results of 1650–1850 nm spectral absorption depths, positions, areas prove this kind of change. As the water content increases, in general, the depth and area of the absorption features at this band decrease, and the absorption position (WAV) is shifted to longer wavelength. All the results indicate that water has a dominant influence on the reflectance in the 1650–1850 nm region. Therefore, it is expected that the spectral absorption features at 1650–1850 nm can be used to evaluate the wheat water status.

Indeed, at the canopy level, Matson *et al.* (1994) correlated AVIRIS data from 1600 nm to 1800 nm to nitrogen concentration estimates and found that 64% of the variance was associated with the water absorption rather than nitrogen. They suggested that any remote sensing algorithm must consider the influence of leaf water.

3.3. *Relationships between RWCs and 1650–1850 nm absorption features*

Card *et al.* (1988) studied the correlation between chemical concentration and reflectance values measured from vegetation leaves. They concluded that chemical concentrations might be predicted from spectra using linear regression models. In order to quantitatively assess the effect of leaf RWC on wheat water deficiencies, the correlations between RWC and three spectral absorption features (DEP, AREA, and WAV) at 1650–1850 nm were conducted by linear regression technique of Sta_win on Microsoft Windows98. In our study, the independent variables are WAV, AREA, and DEP characterizing the absorption features from the 1650 nm to 1850 nm, and the dependent variable is RWC.

Files compatible with specific worksheets were organized for this regression analysis. The files contained the values of DEP, AREA, WAV and corresponding RWC for each spectrum. The predictive equations were simulated through linear regression with 110 sample spectra (absorption features) and corresponding RWC data. Equations (2), (3), (4) and their corresponding coefficients of correlation (R^2)

summarized the results of linear regression analysis. The depth, area, and position of absorption features at 1650–1850 nm presented significant linear relationships with RWCs ($R^2 > 0.73$).

$$\mathrm{RWC}(\%) = 88.94 - 5.88\mathrm{DEP} \quad (R^2 = 0.8718) \tag{2}$$

$$\mathrm{RWC}(\%) = 88.92 - 83.33\mathrm{AEAR} \quad (R^2 = 0.8669) \tag{3}$$

$$\mathrm{RWC}(\%) = -18.69 + 0.0109\mathrm{WAV}(\mathrm{nm}) \quad (R^2 = 0.7347) \tag{4}$$

Figures 3, 4 and 5 are scatterplots between leaf RWC and three spectral absorption features: DEP, AREA and WAV, respectively. The close degree of data points distributing along a straight line (i.e., regression line) in figures 3, 4 and 5 reflects

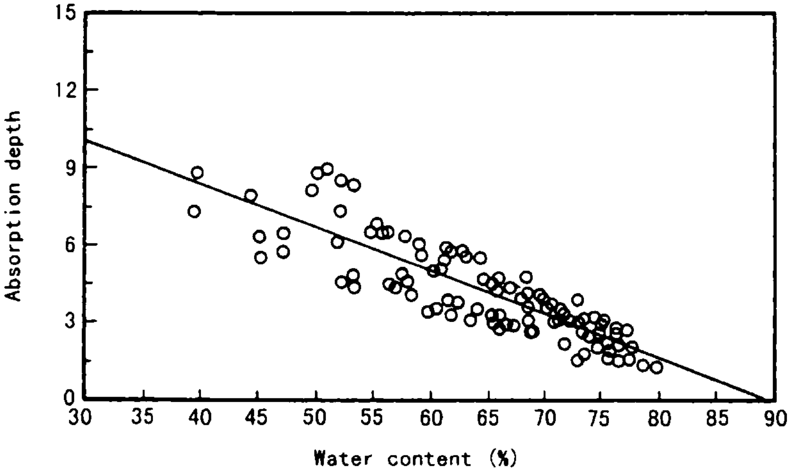

Figure 3. Relationship between the RWC of wheat leaf and the spectral absorption depth at 1650–1850 nm.

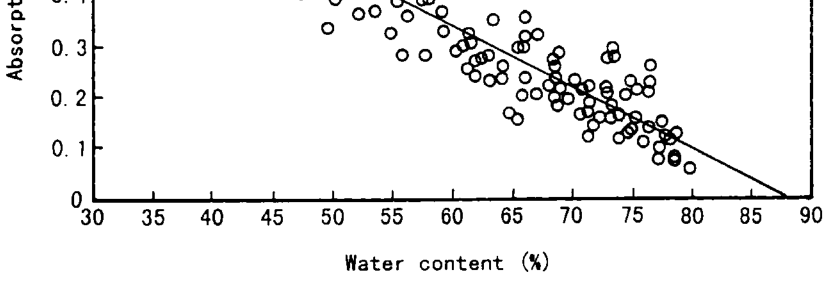

Figure 4. Relationship between the RWC of wheat leaf and the spectral absorption area at 1650–1850 nm.

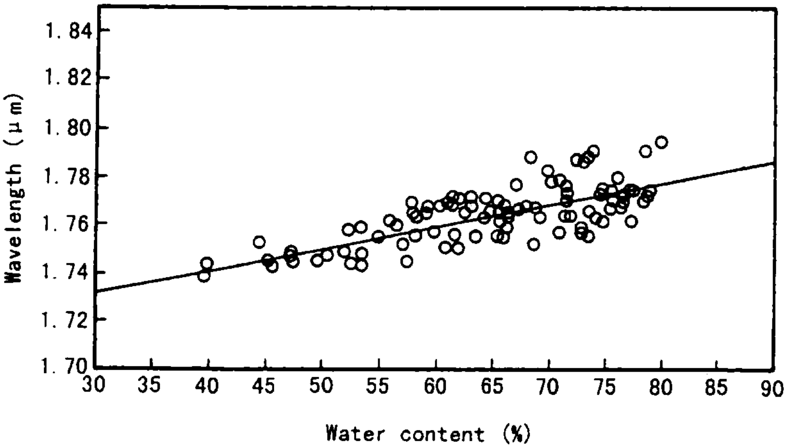

Figure 5. Relationship between the RWC of wheat leaf and the spectral absorption position at 1650–1850 nm.

the leaf RWC predictability with the absorption features. After taking a close look at these plots, we can see that better predictive relationships indeed exist between leaf RWC and absorption features. In this experiment, the RWC of wheat leaf samples varied from the 39.62 to 80.12 percent. For DEP and AREA of absorption features, the troughs at 1650–1850 nm begin to disappear when RWCs are higher than 88.95 percent. In addition, when RWC ranges from 40 to 60 percent (typical RWC of brown senescent leaves), the DEPs and AREAs deviated largely from the regression line, and appeared to be poorer correlations. The range of WAVs was from 1740 nm to 1800 nm while RWCs varied from 40 to 80 percent. And the WAVs dispersed more and more from the regression line beyond 68% of RWC (typical RWC of green fresh leaves).

3.4. *Validation of predictive equations*

A total of 12 wheat leaves were collected during the heading period at the same field sites for the validation of the above predictive equations. The actual leaf RWCs were compared with the RWCs (DRWCs or ARWCs) predicted by DEP or by AREA with equations (2) and (3) (table 1). And the WAVs of 12 samples were also calculated from the spectral normalizing technique, and compared with the calculated results (CWAV) from the predictive equation (4).

Relative errors, Derr (between RWC and DRWC) and Aerr (between RWC and ARWC) were calculated using the following expressions:

$$\mathrm{Derr} = |\mathrm{DRWC} - \mathrm{RWC}|/\mathrm{RWC} \tag{5}$$

$$\mathrm{Aerr} = |\mathrm{ARWC} - \mathrm{RWC}|/\mathrm{RWC} \tag{6}$$

An absolute error, Werr (between WAV and CWAV) was also calculated by the following expression:

$$\mathrm{Werr} = |\mathrm{WAV} - \mathrm{CWAV}| \tag{7}$$

Table 1 presents the calculation results used for the validation of predicted RWCs and WAVs. From the table, according to the predicted results of the 12 samples with

Table 1. Comparison of measured RWCs and WAVs with their predicted values.

RWC	WAV	CWAV	DRWC	ARWC	Derr	Aerr	Werr
78.69	1.797	1.777	75.24	81.07	4.385	3.027	19.98
75.6	1.794	1.774	72.57	77.95	4.008	3.114	9.82
73.8	1.789	1.773	71.01	76.14	3.775	3.168	16.47
71.67	1.784	1.771	69.17	73.99	3.483	3.236	13.43
68.5	1.779	1.768	66.43	70.79	3.015	3.344	11.33
65.86	1.769	1.765	64.15	62.29	2.591	5.415	3.76
60.95	1.752	1.761	59.91	57.34	1.705	5.924	8.74
57.73	1.743	1.758	57.13	54.09	1.042	6.305	14.78
54.87	1.742	1.755	54.66	51.20	0.3878	6.681	13.16
50.31	1.74	1.751	50.72	46.60	0.8088	7.368	10.97
44.36	1.737	1.746	45.58	40.60	2.741	8.477	8.51
38.52	1.734	1.741	41.48	35.82	4.694	9.599	7.17
Average	—	—	—	—	2.720	5.472	11.51

equations (2), (3) and (4), the predicted accuracies are high and indicate that the predictive equations are stable and significant for the estimation of the wheat water status. The average relative errors of RWCs of 12 validation samples predicted with predictive equations (2) and (3) both are lower than 6% of RWCs (2.720% by DEP and 5.472% by AREA, respectively), and the average absolute error of predicted wavelength positions (WAVs) for the 12 samples by equation (4) is 11.51 nm within 1650–1850 nm spectral range.

4. Discussion

The 1650–1850 nm absorption features lie between the major atmosphere water vapor absorption features at 1380 nm and 1900 nm. The reflectance spectra of green vegetation in the 1000–2500 nm region are controlled by both the dominant liquid water and the dry leaf components, such as lignin and cellulose (Gao and Goetz 1994). With a decrease of leaf water content, the dry material accounts a greater proportion of the leaf. The spectral feature of dry leaf components at 1650–1850 nm is generally apparent (Curran 1989). The relative water content of vegetation leaves may be of use in the discrimination of water contents for vegetation communities, so as to evaluate phonologic conditions and identify vegetation status.

Equation (4) is based on the 40–80% RWC range. From this equation, WAV will be inferred to be 1714.83 nm when RWC is 0; and WAV will be 1805.59 nm when RWC is 100%. However, many authors (e.g. Elvidge 1990, Raymond and Roger 1999) pointed out that ground dry leaves of vegetation had an absorption feature either at the 1720 nm or at 1730 nm. Thus, we can explore in the future whether the WAVs of the vegetation leaves at this band will be a constant when the RWC of leaves is below a certain threshold value. On the other hand, figure 2 shows that the slope of spectral curves at 1650–1850 nm also changes with RWC. The derivative analysis technique (Demetriade-shah *et al.* 1990, Gong *et al.* 1992, 1995) may be considered at this band to estimate the wheat leaf water status in the future, i.e., using the relationship between the spectral derivatives at this band and corresponding RWC to estimate the wheat leaf water status.

We have already observed that wheat leaf has a diagnostic spectral absorption feature typically about 10 nm in width (FWHM) at 1650–1850 nm. Conventional sensors (e.g., Landsat MSS and TM) acquire data that smooth to a large extent these reflectance characteristics. However, high-spectral resolution remotely sensed images are now available from imaging spectrometers, which enable the concept of spectral absorption feature characterization to be tested and reflectance or radiance spectra to be produced for each pixel in the scene. Imaging spectrometers acquire images in large numbers (typically over 40) and in narrow (typically 10 to 20 nm in width) contiguous (i.e. matching not overlapping) spectral bands to enable the extraction of reflectance spectra at a pixel scale.

5. Conclusions

Reflectance spectra of wheat leaves were measured in the laboratory in the 350–2500 nm region. The data were analyzed using a linear regression technique. There are good linear relationships between RWC of wheat leaves and the 1650–1850 nm absorption feature parameters: WAV, DEP and AREA. The experimental results from 110 samples indicated that reflectance spectra of wheat leaves in the 1650–1850 nm region were indeed dominated by liquid water contents. With decreasing wheat leaf RWC, the 1650–1850 nm spectral absorption features gradually become obvious. With prediction equations (2), (3), and (4), constructed from 110 samples, the relative errors of predicted RWCs and the absolute error of predicted wavelength position (nm) from 12 validation samples were low ($<6\%$ for RWCs by the depth and area and <12 nm for the wavelength position, respectively).

A field spectroradiometer can provide quantitative information on wheat leaf water deficiencies, which can be translated into a measure of wheat leaf water content with no destruction. These results may be remotely sensed by means of imaging spectrometers that provide image data similar to spectral data measured with a field spectrometer.

Acknowledgments

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