Spectral Reflectance Relationships to Leaf Water Stress

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ABSTRACT: Spectral reflectance data were collected from detached snapbean leaves in the laboratory with a multiband radiometer. Four experiments were designed to study the spectral response resulting from changes in leaf cover, relative water content of leaves, and leaf water potential. Spectral regions included in the analysis were red (band 3, 0.63 to 0.69μm), near infrared (band 4, 0.76 to 0.90μm), and middle infrared (band 7, 2.08 to 2.35μm). Results indicated that the red and middle infrared bands showed sensitivity to changes in both leaf cover and relative water content of leaves. The near infrared was only highly sensitive to changes in leaf cover. Results provided evidence that middle infrared reflectance was governed primarily by leaf moisture content, although soil reflectance was an important factor when leaf cover was less than 100 percent. High correlations between leaf water potentials and reflectance were attributed to covariances with relative water content of leaves and leaf cover.

INTRODUCTION

WATER AVAILABILITY is one of the most critical factors in plant survival, development, and distribution. Traditional techniques for accurate ground-based evaluation of plant water relations are time consuming, costly, and spatially restrictive. Limitations for large-area evaluations of plant water stress may be overcome with the development of remote sensing techniques.

The purpose of this study was to develop laboratory methods which can provide an understanding of the spectral interactions with plant water stress variables. Geometric characteristics of the plant canopy, along with the sun angle and shadow effects, compound the complexity of field measurements for remote sensing of plant water stress. Therefore, a laboratory setting was chosen to hold these factors constant. Study objectives were to

- Examine relationships between spectral reflectance and relative water content of leaves,
- Evaluate the influence of leaf cover changes on spectral and leaf water content relationships, and
- Investigate using spectral reflectance to estimate leaf water potential.

LITERATURE REVIEW

Relationships between spectral reflectance and leaf water content can be either direct or indirect and they are wavelength dependent. For example, reflectance from an individual leaf in the middle infrared region (1.3 to 2.5μm) is largely governed by moisture content of leaves; water absorption is the direct cause for this spectral response (Gates *et al.*, 1965; Knipling, 1970). Relationships between reflectance and leaf water content in the visible (0.4 to 0.7μm) and the near infrared (0.7 to 1.3μm) regions are not direct, but result from co-varying chlorophyll levels (visible) and internal cellular structure (near infrared). Red reflectance increases with leaf moisture stress through an association with a reduction in chlorophyll concentration (Tucker *et al.*, 1980). Near infrared reflectance increases from an individual leaf as leaf moisture stress increases. These increases have been related to the number of reflective surfaces changing as a breakdown of the internal cellular structure occurs (Myers, 1970; Rohde and Olson, 1971).

Most remote sensing of plant moisture stress has been in the form of laboratory leaf spectra investigations. Thomas *et al.* (1966) collected reflectance and relative turgidity data on individual cotton leaves as they dried from a fully turgid condition. Within the 0.4- to 2.5-μm range, relative reflectance increased as turgidity decreased with the visible spectrum responding least. Thomas *et al.* (1966; 1971) concluded that the curvilinear nature of their regression equations indicated that relative turgidity must be less than 70 or 80 percent to cause predictable changes in reflectance. Olson (1967) found that at wavelengths of 1.55, 2.05, and 2.50μm, reflectance increased almost linearly with decreases in tree leaf moisture content (percent of over-dry weight). Rohde and Olson (1971) reported inverse curvilinear relationships between reflectance and tree leaf moisture in the middle infrared region (1.3 to 2.5μm). Sinclair *et al.* (1971) obtained reflectance spectra from the leaves of six agronomic crops and reported leaf water loss caused increases in reflectance in the 1.3- to 2.6-μm region. Thomas and Gausman (1977) could not establish a pattern between water content of individual leaves and reflectance in the 0.40- to 0.75-μm wavelength interval. With consideration given to atmospheric windows,

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Tucker (1980) concluded that the 1.55- to 1.75-μm interval was the best band within the 0.7- to 2.5-μm spectral region for monitoring plant water stress from space platforms.

Changes in canopy geometry and in the soil background exposed to the sensor should be addressed in describing reflectance from a water-stressed plant canopy. Curran and Milton (1983) reported both red and near infrared reflectance increased during canopy wilting through an increase in the area of the highly reflective substrate exposed to the sensor. Huete *et al.* (1985) found that reflectance increased in the near infrared, but it decreased in the visible and middle infrared with increasing amounts of canopy coverage over various soil types.

Thomas *et al.* (1966) and Bauer *et al.* (1981) discovered that the spectral response in the middle infrared was related more closely to absolute plant water content (g/m^2) than to relative water content (relative turgidity). Middle infrared reflectance was discovered to be asymptotic at relatively low levels of canopy water (Bauer *et al.*, 1981). Ripple (1985) reported a significant correlation ($r = -0.91$) between logarithmic transformations of absolute plant water and *in situ* reflectance in the 2.08- to 2.35-μm band with the asymptote occuring at a moderate level of plant canopy water (~520g/m^2).

In a field radiometry study, Holben *et al.* (1983) found the near infrared (0.76 to 0.90μm) to be more responsive than the red (0.63 to 0.69μm) or middle infrared (1.55 to 1.75μm) for detecting plant water stress in soybeans. They concluded that the superiority of the near infrared was due to the near-infrared sensitivity to changes in canopy leaf geometry and canopy cover caused by leaf wilting. Jackson and Ezra (1985) also found reflectance was sensitive to canopy geometry changes which accompanied water stress in cotton. They reported that all spectral bands measured reacted rapidly to water stress in the cotton canopy. The visible and thermal infrared regions showed larger changes than the near infrared region.

The work reported here was intended to extend previous research by determining, through controlled experiments, the sensitivity of selected spectral bands to leaf cover independent of leaf water content and to leaf water content independent of leaf cover. Previous studies describing relationships between reflectance and leaf water potential were not discovered in this literature search.

MATERIALS AND METHODS

Spectral reflectance data were collected from snapbean leaves (*Phaselus vulgaris* L. cv.'Blue Lake') grown in a greenhouse. Laboratory spectra were obtained using a Barnes Modular Multiband Radiometer interfaced with an Omnidata data logger. A barium sulfate coated reference standard was used for calibration. Illumination was provided by a 500-watt tungsten halogen lamp with a wide beam spread (Hubbell model QL-505, Harvey Hubbell Inc., Anaheim, California). The radiometer was positioned normal to the target and the illumination angle was 45°. The three spectral regions included in the analysis were red (band 3, 0.63 to 0.69μm), near infrared (band 4, 0.76 to 0.90μm), and middle infrared (band 7, 2.08 to 2.35μm).

Results of four experiments are reported upon here. Experiments 1 and 2 were designed to study reflectance changes resulting from changes in leaf cover (LC). In the third experiment, LC was held constant while leaf relative water content (RWC) was allowed to vary. The fourth experiment involved concurrent changes in LC and RWC.

Experiment 1 consisted of (1) hydrating a set of detached leaves in water, (2) laying these leaves on a soil tray within the field of view (FOV) of the radiometer, (3) obtaining spectra, (4) removing an individual leaf, (5) obtaining spectra, and (6) repeating the above procedure until all of the leaves were removed from the soil tray.

Experiment 2 involved allowing the leaves used in experiment 1 to dehydrate at room temperature (21°C) for three hours and then collecting spectra following steps 2 through 6 in experiment 1.

Experiments 3 and 4 involved (1) hydrating a set of detached bean leaves in water and obtaining a full turgor weight; (2) laying these leaves on a soil tray both within and outside the FOV of the radiometer; (3) periodically obtaining spectra as leaves were dehydrating; (4) concurrently with the collection of spectra, collecting a leaf sample from outside the field of view for leaf moisture content and leaf water potential (WP) determinations; and (5) repeating the above procedure until a wide range of leaf moisture levels was obtained.

Leaf moisture stress variables were leaf WP and RWC. WP was measured with a pressure chamber made by PMS Instruments using methods developed by Waring and Cleary (1967). WP is defined as the potential energy per unit mass of water with reference to pure water at zero potential (Coombs and Hall, 1982). WP is measured with a pressure chamber and is usually expressed in units of pressure with the reference system set to zero. The pressure chamber has proven to be a successful instrument for measuring moisture stress, with pressure increasing as moisture stress increases. RWC was expressed as a percent in relation to the amount of moisture held in a fully turgid leaf: i.e.,

$$\mathrm{RWC} = [(\mathrm{FW} - \mathrm{DW}) / (\mathrm{SW} - \mathrm{DW})] \times 100$$

where FW is fresh weight, DW is oven-dry weight, and SW is saturated weight of the leaf.

The area of soil covered by leaves was obtained using a dot count procedure on vertical photographs which were taken concurrently with spectral data. The medium yellow-brown background soil (2.5Y-4/4 Munsell code) was a dry greenhouse mixture of 1/3 sand, 1/3 loam, and 1/3 peat.

Table 1 contains a summary of the variables collected for the four experiments. Experiments 1 and

TABLE 1. SUMMARY OF LEAF MOISTURE/PLOT VARIABLES.

	Mean	Minimum	Maximum	Coefficient of Variation
Experiment 1 (Hydrated Leaves)				
Leaf Cover (%)	57.9	00.0	98.0	0.52
Relative Water Content (%)	—	76.9	100.0	—
Experiment 2 (Dehydrated Leaves)				
Leaf Cover (%)	46.7	00.0	86.0	0.55
Relative Water Content (%)	—	27.5	32.1	—
Experiment 3 (Constant Leaf Cover)				
Leaf Cover (%)	100.0	100.0	100.0	0.00
Relative Water Content (%)	59.2	30.6	93.3	0.35
Leaf Water Potential (MPa)	−0.88	−1.69	−0.14	0.57
Experiment 4 (Variable Leaf Cover)				
Leaf Cover (%)	85.0	72.5	93.8	0.08
Relative Water Content (%)	69.8	42.3	10.0	0.28
Leaf Water Potential (MPa)	−0.99	−1.50	−0.15	0.46

2 involved changing LC while holding RWC relatively constant. This procedure was conducted for both hydrated (Experiment 1) and dehyrated (Experiment 2) leaves. Experiment 3 consisted of two or three layers of snapbean leaves within the FOV of the radiometer. This insured that LC would not drop below 100 percent because the leaves shrink as they dehydrate. In the fourth experiment, one layer of snapbean leaves was used with LC varying from 93.8 percent fo 72.5 percent during the experiment.

An attempt was made to verify that the average rate of dehydration of the leaves inside the field of view was the same as for the leaves that were collected for weighing outside the field of view. A test was conducted in which ten leaves were placed in the field of view and ten outside the field of view. RWC and WP were collected from these ten pairs at different leaf moisture levels (98.7 percent to 41.3 percent RWC). The RWC and WP of the leaves were examined for differences by using the student's *t*-test (Snedecor and Cochran, 1980). The null hypothesis that there were no significant differences could not be rejected ($P \geq 0.3$). It was concluded that the rate of dehydration of the leaves inside the field of view was not significantly different from the rate of those outside the field of view.

A test to verify the rate of dehydration of the stacked leaves in the FOV for Experiment 3 was not feasible. To minimize differences in dehydration rates in Experiment 3, the leaves that were collected for weighing were stacked in a similar fashion to the leaves inside the field of view of the radiometer.

For the correlations reported here, there is a degree of observational interdependence or autocorrelation in the data sets. Autocorrelation is common in remote sensing data sets that are spatially or temporally dependent upon successive values (Ripple *et al.*, 1986). Autocorrelation does not affect the estimation of the regression equation (the equation is unbiased), but it does cause the correlation coefficient (r) to be overestimated (Pindyck and Rubinfeld, 1981). Therefore, the correlation coefficients presented in the following section were intended to be used only for relative comparisons among treatments and spectral bands included here.

RESULTS AND DISCUSSION

The results of the four experiments are presented in the following sections. The first section discusses the effects of LC on reflectance; the second section examines the effects of RWC on reflectance; the third section discusses the effects of concurrent changes in LC and RWC on reflectance; and the last section considers relationships between reflectance and leaf WP.

LEAF COVER EFFECTS

Relationships between reflectance and LC for Experiments 1 and 2 are shown in Figures 1a and 1b. The spectral response of bands 3, 4, and 7 are shown in the left column for hydrated leaves (Figure 1a) and in the right column for dehydrated leaves (Figure 1b). The inverse response of band 3 to changes in hydrated LC was similar to that of dehydrated LC, although the slope of the regression line was steeper for hydrated leaves. This was probably because the hydrated leaves had higher levels of chlorophyll and higher levels of red energy absorption that resulted in lower leaf reflectance values. Band 4 showed very similar direct responses to changes in both hydrated and dehydrated LC. This indicates a low sensitivity of the near infrared (band 4) energy to leaf moisture content. In band 7, reflectance was inversely related to hydrated LC and directly related to dehydrated LC. These differing relationships were caused by changes in middle infrared (band 7) leaf reflectance in relation to reflectance from the soil. Reflectance from hydrated leaves was lower than reflectance of the soil, causing an inverse relationship. These levels of lower leaf reflectances were attributed to high levels of absorption by leaf water. Conversely, the dehydrated

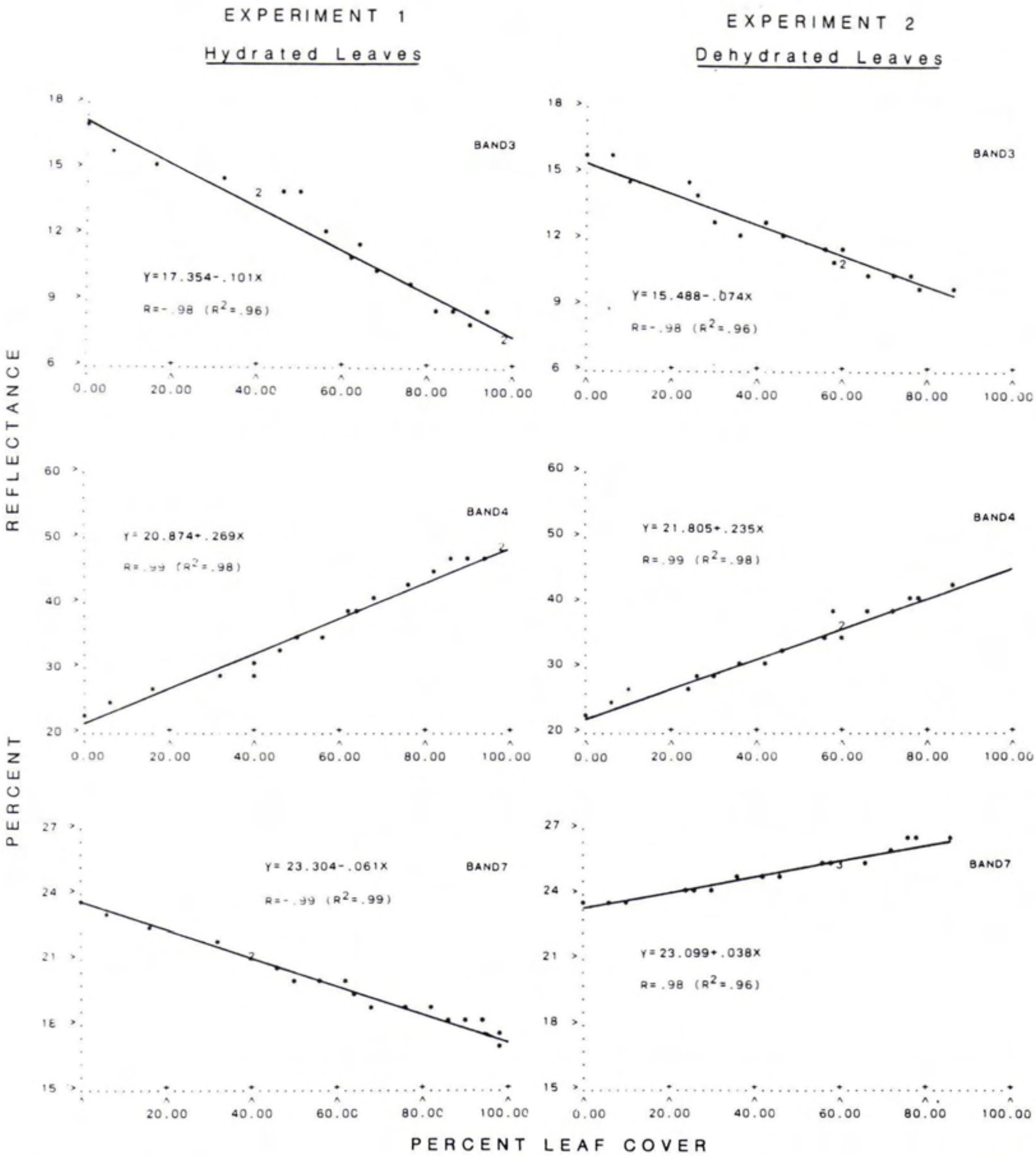

FIG. 1. (a) Scatter diagrams for experiment 1 showing relationships between leaf cover of hydrated leaves and reflectance of band 3 (top left), band 4 (middle left), and band 7 (bottom left). (b) Scatter diagrams for experiment 2 showing relationships between leaf cover of dehydrated leaves and reflectance of band 3 (top right), band 4 (middle right), and band 7 (bottom right).

leaf reflectance was higher than soil reflectance because there was very little absorption by water. These results show that the relationship between middle infrared reflectance and leaf cover was dependent upon both leaf RWC and soil background reflectance characteristics. These results also provide evidence that middle infrared reflectance from these green leaves was primarily governed by leaf moisture.

LEAF WATER CONTENT EFFECTS

Figure 2a illustrates the relationships between RWC and reflectance when LC was held constant at 100 percent for Experiment 3. Band 3 reflectance exhibited an inverse linear relationship with RWC. These results were probably due to a reduction in chlorophyll as the leaves dried. The band 4 reflectance relationship with RWC was inverse, but relatively weak. Band 4 reflectance increased slightly as RWC decreased. This increase may have been caused by cellular changes occurring in the leaves (Sinclair *et al.*, 1971). Band 7 exhibited an inverse linear relationship with RWC. As expected, reflectance increased as leaf moisture

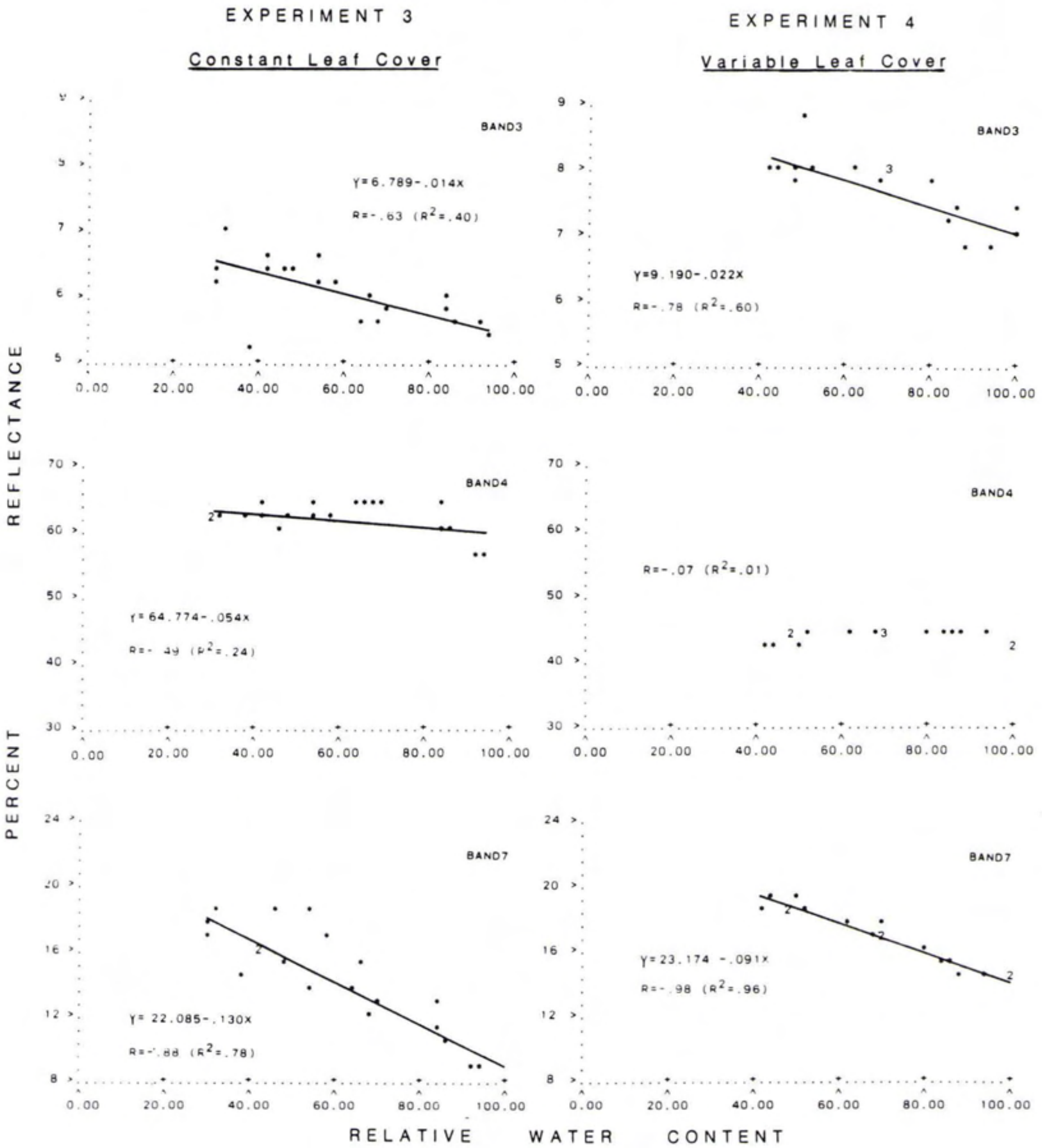

FIG. 2. (a) Scatter diagrams for experiment 3 showing relationships between RWC and reflectance of band 3 (top left), band 4 (middle left), and band 7 (bottom left). Leaf cover was held constant at 100 percent. (b) Scatter diagrams for experiment 4 showing relationships between RWC and reflectance of band 3 (top right), band 4 (middle right), and band 7 (bottom right). Leaf cover varied from 93.8 percent to 72.5 percent.

decreased. This provided additional evidence that the middle infrared reflectance was strongly governed by the amount of leaf water.

Leaf Cover and Water Content Effects

Figure 2b illustrates relationships between RWC and reflectance when RWC and LC were allowed to vary concurrently (Experiment 4). Leaf cover varied from 93.8 percent to 72.5 percent as a result of leaf dehydration and shrinkage during the experiment. The correlation coefficient between RWC and band 3 reflectance was higher in Experiment 4 ($r = -0.78$) than in Experiment 3 ($r = -0.63$). This was attributed to both decreases in LC and RWC having the effect of increasing band 3 reflectance. Band 4 reflectance remained relatively unchanged as RWC and LC decreased. This response may have been caused by off-setting biophysical relationships relating to RWC and LC. Band 4 reflectance was inversely related to RWC and directly related to LC. As with band 3, the correlation coefficient between RWC and band 7 reflectance was higher in Experiment 4 ($r = -0.98$)

TABLE 2. CORRELATION COEFFICIENTS (r) BETWEEN LEAF WATER POTENTIAL (WP) AND SPECTRAL BANDS, RELATIVE WATER CONTENT (RWC), AND LEAF COVER (LC). THE SPECTRAL/WP RELATIONSHIPS WERE INVERSE BECAUSE WP WAS RECORDED AS A NEGATIVE NUMBER.

	Experiment 3 (WP)	Experiment 4 (WP)
Band 3	−0.60	−0.82
Band 4	−0.38	−0.29
Band 7	−0.89	−0.93
RWC	0.84	0.91
LC	—	0.77

than in Experiment 3 ($r = -0.88$). This stronger relationship was also attributed to both decreasing LC and decreasing RWC causing higher band 7 reflectance.

LEAF WATER POTENTIAL

Significant correlations were found between the spectral bands and leaf water potentials (Table 2). Leaf water potential reflects the status of water within the plant through an integration of factors involving water availability, osmotic potential, resistance to water movement within the plant, and the demands for transpiration. For both Experiments 3 and 4, the middle infrared band 7 had the highest correlations with leaf water potentials. The spectral-leaf water potential correlations can be attributed primarily to a covariance with RWC for the middle infrared (band 7), and to a covariance with LC for the red (band 3) (Table 2). The near infrared (band 4) showed the lowest correlations with leaf water potentials.

It may be desirable to use leaf water potential as a substitute for relative water content as a primary variable for studies involving remote sensing of plant water stress. Obtaining relative leaf water content is time consuming, because leaves must be harvested, weighed, hydrated, re-weighed, over-dried, and reweighed. Relative water content could be predicted through correlations with leaf water potential (Richardson and McKell, 1980).

CONCLUSIONS

Under the conditions of this study, the following conclusions can be made concerning relationships between the spectra and the leaf/plot variables:

- Red reflectance (band 3) was sensitive to both LC and RWC.
- Near infrared reflectance (band 4) was strongly related to LC and weakly related to RWC.
- Middle infrared reflectance (band 7) was highly correlated with LC and RWC.
- Evidence was provided that linked middle infrared reflectance (band 7) directly to leaf moisture content.
- The reflectance of the background soil was a very important factor influencing the reflectance-RWC relationships when LC was variable. The relationship between middle infrared reflectance and LC changed from inverse to direct after a significant decrease in leaf RWC.
- Leaf WP was strongly related to both middle infrared and red reflectance. These correlations were attributed to covariances with RWC and LC, respectively.

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