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Measurement of Leaf Relative Water Content by Infrared Reflectance

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From basic considerations and Beer's law, a leaf water content index incorporating reflectances of wavelengths from 0.76 to 0.90 μm and from 1.55 to 1.75 μm (Landsat Thematic Mapper Bands TM4 and TM5, respectively) was developed that relates leaf reflectance to leaf relative water content. For the leaf succulent, *Agave deserti*, the leaf water content index was not significantly different from the relative water content for either individual leaves or an entire plant. Also, the relative water contents of intact plants of *Encelia farinosa* and *Hilaria rigida* in the field were estimated by the leaf water content index; variations in the proportion of living to dead leaf area could cause large errors in the estimate of relative water content. Thus, the leaf water content index may be able to estimate average relative water content of canopies when TM4 and TM5 are measured at a known relative water content and fraction of dead leaf material.

Introduction

Water stress caused by drought limits plant productivity and crop yields by reducing photosynthesis and leaf growth (Boyer, 1982; Bradford and Hsiao, 1982). Detection of water stress is a major application of remote sensing (Knipling, 1970; Wiegand et al., 1972; Goetz et al., 1983; Kanemasu et al., 1985). Techniques for remote sensing of water stress include determination of canopy temperature (Idso et al., 1981; Jackson, 1982) or determination of vegetation indices that use red and near-infrared reflectances (Wiegand et al., 1972; Thompson and Wehmanen, 1979; Jackson et al., 1983). Leaves reflect strongly in the near infrared from 0.7 to 1.2 μm, but less strongly in the middle infrared from 1.3 to 2.4 μm because of the absorption at the latter wavelengths by leaf water (Thomas et al., 1971; Gausman et al., 1970; Gates, 1980; Tucker, 1980). Thematic Mapper Bands 4 and 5 (TM4 and TM5) cover the infrared wavelengths from 0.76 to 0.90 μm and from 1.55 to 1.75 μm, respectively, so that changes in the amount of leaf water caused by drought can be detected by changes in middle-infrared reflectances (Gausman et al., 1970; 1978; Thomas et al., 1971; Tucker, 1980). Ratios formed by these two bands are highly correlated with the

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amount of leaf water (Hardisky et al., 1983; Rock et al., 1985), but the relationship between reflectance changes and any physiologically significant measure of plant water stress is not known. In this study, we derive and test a leaf water content index (LWCI) that equates changes of infrared reflectances to leaf relative water content (RWC), an important measure of water stress.

Development of Leaf Water Content Index

The degree of plant stress caused by drought can be physiologically quantified by either leaf water potential (Ψ^{leaf}) or RWC (Bradford and Hsiao, 1982; Nobel, 1983; Sinclair and Ludlow, 1985). Ψ^{leaf} is the difference in chemical potential between leaf water and pure water divided by the partial molal volume of water, and represents the driving force for water movement from the soil into a plant (Nobel, 1983). RWC is the ratio of the water volume (V) in a leaf to the maximum water volume in that leaf at full turgor (V_{FT}), where RWC equals unity. RWC can control plant response to water stress (Bradford and Hsiao, 1982; Sinclair and Ludlow, 1985). For a given leaf, there generally is a one-to-one relationship between Ψ^{leaf} and RWC, which can be portrayed as a pressure-volume curve (Nobel, 1983; Nobel and Jordan, 1983).

The volume of water in a leaf or canopy is equal to an equivalent thickness of water averaged over the leaf area (Gausman et al., 1970; Tucker, 1980). By Beer's law, absorbance of infrared radiation by leaf water (A) is equal to the product of the equivalent water thickness (l), the extinction coefficient (ε_w), and the concentration of water (c_w, taken as 55.6 mol/L). The ratio of leaf absorbance to leaf absorbance at full turgor (A/A_{FT}) is equal to the ratio of equivalent thicknesses (l/l_{FT}) because ε_w and c_w cancel out. The equivalent thickness of water times the leaf area in the field of view of an instrument is equal to the volume of leaf water in that field of view. Therefore, A/A_{FT} is equal to the ratio of water volumes averaged over the leaf area (V/V_{FT}), which is RWC. Absorbance is usually calculated as $-\log(\text{transmittance})$ with reflectance being set to zero; it can also be calculated as $-\log(1-a)$, where 1 minus the absorptance a is equal to the sum of transmittance and reflectance (Nobel, 1983).

TM4 has the maximum reflectance from a green leaf of the six shortwave Thematic Mapper bands, whereas reflectance of TM5 is reduced because of absorption by water (Knipling, 1970; Tucker, 1980). For thick leaves with negligible transmittance, the difference between reflectance of TM5 for a dry leaf and when the leaf is fresh should be equal to the absorptance by water in that leaf. Furthermore, reflectance of TM5 for dry leaves is almost exactly equal to reflectance of TM4 (Knipling, 1970; Thomas et al., 1971; Rock et al., 1985), so that the difference between the reflectances TM4 and TM5 for the fresh leaf should also be equal to the water absorptance in that leaf. Therefore, we propose that RWC equals a leaf water content index (LWCI) based on the ratio of absorbances (A/A_{FT}) as follows:

$$\text{LWCI} = \frac{-\log[1-(\text{TM4}-\text{TM5})]}{-\log[1-(\text{TM4}_{\text{FT}}-\text{TM5}_{\text{FT}})]}, \tag{1}$$

where $TM4_{FT}$ and $TM5_{FT}$ are the reflectances of TM4 and TM5 at full turgor. For thin leaves, transmittance can equal a constant proportion of reflectance (Gates, 1980), in which case the reflectances can be increased accordingly.

Materials and Methods

Leaves of *Agave deserti* Engelm. (Agavaceae), a leaf succulent whose leaves are arranged in a basal rosette, were excised on two occasions from five different plants located in the field at the Philip L. Boyd Deep Canyon Desert Research Center near Palm Desert, CA (850 m elevation, 33°38′N latitude, 116°24′W longitude). The leaves (about 0.4 m long and 0.08 m wide) were placed in water under subdued light until no further weight increases occurred due to the uptake of water (after 3 days). The final weight was defined as the weight at full turgor (W_{FT}). The lower side (abaxial) of the leaves was abraided to reduce the cuticular resistance to water vapor diffusion. Leaves were laid flat on a black plastic sheet, and the reflectances of the upper side (adaxial) of the leaves were measured between 11:30 AM and 12:30 PM PST over the next 6 days in the field. Two measurements per leaf per day were used to obtain a mean reflectance. Reflectances compared to a Corning Fiberfrax standard were measured using a Barringer Research Ltd. MK I Hand Held Ratioing Radiometer fitted with filters to simulate TM bands and with a rectangular field of view of about 0.2×0.06 m. The reflectances of TM4 and TM5 at full turgor were used for $TM4_{FT}$ and $TM5_{FT}$; then TM4 and TM5 measured on the other days were used to calculate LWCI. The leaf fresh weight (W_F) was determined each day; the dry weight (W_D) was determined after drying the leaves in an oven at 80°C. RWC was calculated as $(W_F - W_D)/(W_{FT} - W_D)$ times the density of water.

Reflectances from two intact plants of *A. deserti*, one intact plant of *Encelia farinosa* Gray (Asteraceae; a desert shrub), and one intact plant of *Hilaria rigida* (Thurb.) Benth ex Scribn. (Poaceae; a desert bunchgrass) were measured in the field 1 m above the top of the plants using the radiometer. Reflectances were measured between 11:30 AM and 12:30 PM on five dates: 19 February 1985, 29 March 1985, 10 May 1985, 14 June 1985, and 29 July 1985. Substantial rainfall occurred in February, March, and July of 1985, so the soil was moist ($\Psi^{soil} > -0.5$ MPa) on the measurement dates of these months, whereas the soil was dry ($\Psi^{soil} < -4.0$ MPa) in May and June of 1985. Two reflectance measurements per plant were used to obtain a mean reflectance for each date. To obtain the same field of view for each measurement, metal stakes were used to align the radiometer on each plant. RWC was estimated from Ψ^{leaf} using pressure–volume curves for each species in the field (Nobel and Jordan, 1983). Ψ^{leaf} of *A. deserti* was measured using Wescor, Inc. (Logan, UT) PCT-55-15 soil thermocouple psychrometers inserted into the succulent leaves; Ψ^{leaf} of *E. farinosa* and *H. rigida* was measured using a PMS Instruments (Corvallis, OR) PMS 1000 pressure chamber. To compare leaf reflectances of *A. deserti* with reflectances of the intact plant, one leaf was excised from one of the plants on 29 March 1985 and on 14 June 1985.

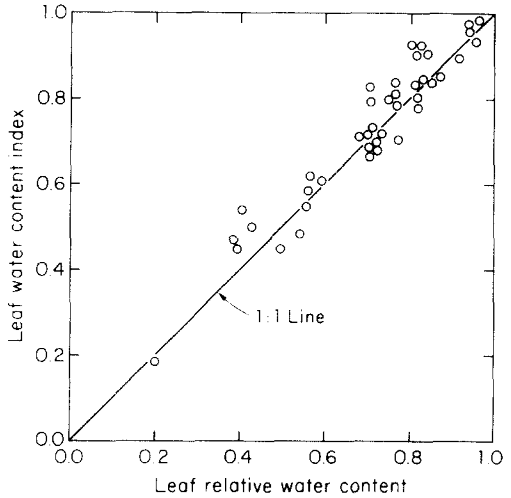

FIGURE 1. Leaf water content index (LWCI) of *Agave deserti* versus leaf relative water content (RWC). For each of ten leaves, the reflectances TM4 and TM5 at an RWC of 100% (full tugor) were used for $TM4_{FT}$ and $TM5_{FT}$; then TM4 and TM5 measured on the next six days were used to calculate LWCI. The regression equation (±s.e. on coefficients) is: LWCI = 0.955 (±0.060) × RWC + 0.056 (±0.043), $r^2 = 0.87$. The goodness-of-fit to the hypothesized 1:1 line was 0.84.

Results and Discussion

The hypothesis that the LWCI was equal to RWC was tested using detached leaves of *Agave deserti* (Fig. 1). Leaves of *A. deserti* are thick, so that transmittance is negligible (Gates, 1980), and large enough to cover the field of view of the hand-held ratioing radiometer. Moreover, the reflectance of TM5 for dried leaves of *A. deserti* was about equal to that of TM4 (data not shown), so that all of the assumptions necessary to derive the LWCI were met. The regression equation was not significantly different from the hypothesized 1:1 line (Fig. 1), indicating that the LWCI was about equal to RWC.

Leaves in the field are generally not at full turgor. If TM4 and TM5 are measured at a known RWC, then the difference, $TM4_{FT} - TM5_{FT}$, can be calculated by setting LWCI equal to the known RWC, and RWC at other times can then be estimated from reflectance data using LWCI [Eq. (1)]. For an *A. deserti* in the field during a wet and a dry season (Table 1), the nonstressed leaf had an RWC of about 0.93 whereas the stressed leaf had an RWC of about 0.79. The difference, $TM4_{FT} - TM5_{FT}$, was calculated from the nonstressed leaf reflectances (Table 1), assuming that LWCI equaled the RWC of 0.93, which led to a LWCI of 0.77 for the stressed leaf, similar to the measured RWC.

The above approach can be used to estimate the average RWC for an intact plant of *A. deserti*. Using the reflectance measurements for a nonstressed plant to calculate the difference, $TM4_{FT} - TM5_{FT}$, the LWCI of the stressed plant was 0.76, similar to the measured RWC of about 0.79. Reflectances for single leaves were much higher for all bands than reflectances for the intact plant for either the wet season or the dry season (Table 1), because variable angles of incidence and nonilluminated areas affect the infrared reflectance. For the second *A. deserti*, LWCI was similar to and followed the pattern of changes in RWC estimated from Ψ^{leaf} (Table 2). Thus, the LWCI approach is applicable to intact plants of *A. deserti*, but reflectances of TM4 and TM5 must be measured in a similar manner as the reflectances used for $TM4_{FT}$ and $TM5_{FT}$.

Plant water stress substantially increased the reflectances TM5 and TM7 for both leaves and the intact plant but increased the reflectance TM1 considerably less (Table 1). The reflectances TM2 and TM3 decreased slightly for the leaves but increased for the plant (Table 1).

TABLE 1 Effect of Water Stress on Reflectances of Thematic Mapper Bands for Leaves and Entire Rosettes of *Agave deserti*

THEMATIC MAPPER BAND NUMBER AND WAVELENGTH INTERVAL (μm)	REFLECTANCE			
	NONSTRESSED leaf	WATER-STRESSED leaf	NONSTRESSED plant	WATER-STRESSED plant
TM1 (0.45–0.52)	0.343	0.356	0.045	0.068
TM2 (0.52–0.60)	0.493	0.483	0.069	0.083
TM3 (0.63–0.69)	0.383	0.373	0.040	0.050
TM4 (0.76–0.90)	0.859	0.850	0.388	0.372
TM5 (1.55–1.75)	0.262	0.371	0.042	0.085
TM7 (2.08–2.35)	0.116	0.167	0.018	0.037

TABLE 2 Effect of Water Stress on Leaf Water Status and Reflectances of Thematic Mapper Bands 4 and 5 for Intact Plants of *Agave deserti*, *Encelia farinosa*, and *Hilaria rigida*

SPECIES	DATE (1985)	Ψ^{leaf} (MPa)	TM4	TM5	LWCI	RWC
A. deserti	19 Feb	-0.5	0.472	0.077	—[a]	0.90
	29 Mar	-0.4	0.481	0.071	0.94	0.92
	10 May	-0.7	0.491	0.130	0.80	0.86
	14 Jun	-1.1	0.497	0.156	0.75	0.78
	29 Jul	-0.7	0.484	0.087	0.91	0.86
E. farinosa	19 Feb	-1.3	0.389	0.330	—[a]	0.77
	29 Mar	-1.9	0.387	0.332	0.72	0.66
	10 May	-2.4	0.398	0.357	0.53	0.57
	14 Jun	-3.8	0.376	0.370	0.08	0.31
	29 Jul	-1.9	0.383	0.351	0.41	0.66
H. rigida	29 Mar	-1.5	0.286	0.259	—[a]	0.66
	10 May	-3.1	0.246	0.230	0.39	0.30
	14 Jun	< -4.0	0.282	0.278	0.10	0.00
	29 Jul	-1.9	0.256	0.234	0.54	0.57

[a] Data used to calculate ($TM4_{FT} - TM5_{FT}$) by setting LWCI equal to RWC in Eq. (1).

Thus, the amount of leaf water for *A. deserti* cannot be unambiguously determined from TM2 or TM3. Whereas TM7 had a larger percent change than TM5, the absolute change was small (Table 1), so that TM5 is preferable for determining the absorptance by water (Tucker, 1980; Rock et al., 1985).

Even though *A. deserti* differs in metabolism and leaf anatomy (Nobel and Jordan, 1983), the LWCI approach developed with *A. deserti* may be applicable to other plants. For *Encelia farinosa*, LWCI was similar to RWC on 29 March and 10 May 1985 but not on 14 June and 29 July 1985 (Table 2). The leaves of *E. farinosa* produced in the spring die and remain on the stem; moreover, leaves produced in the summer are small and have a dense pubescence, which reflects considerably in the visible (Ehleringer and Björkmann, 1978). Thus, the formation of morphologically different leaves and the retention of old dead leaves probably changed $TM4_{FT} - TM5_{FT}$, which in turn caused large deviations between LWCI and RWC for *E. farinosa* (see Weiser et al., 1984). *Hilaria rigida* has more standing dead shoots than living shoots, which may have caused the reflectances of TM5 to be close to those of TM4 for the four dates measured (Table 2). Even though the dead shoots were not averaged into RWC of the intact plant (but were included in the calculation of $TM4_{FT} - TM5_{FT}$ using the 29 March 1985 data), LWCI followed the pattern of change in RWC.

For some species, the above approach may not be appropriate because reflectances in the near- and middle-infrared wavelengths are not affected for changes in RWC from 0.9 to 0.8, but have large changes for RWC from 0.8 to 0.7 (Knipling, 1970). For these species, the onset of water stress occurs at an RWC of 0.8, so that reflectance measurements may not detect the onset of water stress. However, it should be noted that LWCI is a ratio of logarithms, so that small changes in reflectance may result in large changes of LWCI over the range of RWC from 1.0 to 0.8.

Although LWCI was developed for leaves with negligible transmittance, it can be applied to plant canopies (Table 2). One advantage of using LWCI for the detection of water stress is that it is based on leaf relative water content, whereas the use of red/near-infrared and thermal-infrared measurements are based on manifestations of water stress, namely reduced chlorophyll absorptance and increased leaf temperatures (Tucker, 1980; Jackson, 1982). The LWCI approach requires knowledge of the reflectances of TM4 and TM4 at a known RWC, which can be obtained from ground studies used in conjunction with satellites or aircraft for the remote sensing of water stress.

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