REMOTE SENS. ENVIRON. 30:43–54 (1989)

Detection of Changes in Leaf Water Content Using Near- and Middle-Infrared Reflectances

E. Raymond Hunt, Jr.

Jet Propulsion Laboratory, California Institute of Technology

Barrett N. Rock

Institute for the Study of Earth, Oceans and Space, University of New Hampshire

Detection of plant water stress by remote sensing has been proposed using indices of Near-Infrared (NIR, 0.7–1.3 μm) and Middle-Infrared (MIR, 1.3–2.5 μm) wavelengths. The first objective of this study was to test the ability of the Leaf Water Content Index (LWCI) to determine leaf Relative Water content (RWC) of different species with different leaf morphologies. The second objective was to determine how the Moisture Stress Index (MSI; MIR/NIR) varies with RWC and the Equivalent Water Thickness (EWT). Reflectance factors at 0.82 μm and 1.6 μm were measured on leaves of Quercus agrifolia *(sclerophyllous leaves),* Liquidambar styraciflua *(hardwood deciduous tree leaves),* Picea rubens *and* Picea pungens *(conifer needles), and* Glycine max *(herbaceous dicot leaves) as they dried on a laboratory bench. RWC and EWT were measured concurrently with the reflectance measurements. The results showed that LWCI was equal to RWC for the species tested. However, the results of a sensitivity analysis indicated the reflectances at 1.6 μm for two different RWC must be known for accurate prediction of unknown RWC; thus the LWCI is impractical for field applications. MSI was linearly correlated to RWC with each species having a different regression equation and to $\log_{10}$ EWT with data of all species falling on the same regression line. Because EWT is correlated with leaf area index, MSI should also be correlated with leaf area index. Assuming that the linear regression equation of MSI to EWT can be applied to canopies, then the minimum significant change of RWC that can be detected is 52%. For most plants, the natural variation in RWC from water stress is only about 20%, so that we conclude that indices derived from NIR and MIR reflectances cannot be used to remotely-sense water stress.*

Address correspondence to Dr. E. Raymond Hunt, Jr., School of Forestry, University of Montana, Missoula, MT 59812.

Received 28 June 1988; revised 19 September 1989.

0034-4257/89/$3.50

655 Avenue of the Americas, New York, NY 10010

INTRODUCTION

Detection of plant water stress caused by drought is a major goal for remote sensing (Bauer et al., 1986; Jackson et al., 1986). Interactions of vegetation with radiation, particularly for Near-Infrared wavelengths (NIR, 0.7–1.3 μm) and Middle-Infrared wavelengths (MIR, 1.3–2.5 μm), depend in part on the volume of water in leaf cells. Methods for detection of water stress by remote sensing based on plant physiology are desirable because these methods can be readily used on different vegetation types with little adjustment (Jackson, 1982; Hunt et al., 1987).

One such method is the Leaf Water Content Index (LWCI, see Background for brief description), which uses NIR and MIR reflectances to determine leaf Relative Water Content, RWC (Hunt et al., 1987). The LWCI is equal to RWC for a leaf succulent, *Agave deserti*, and was somewhat successful in predicting seasonal changes of RWC for whole plants (Hunt et al., 1987), but it is not known if the LWCI can be applied to other species for which the assumptions necessary to derive LWCI do not hold. Therefore, the first objective of this study was to test the ability of the LWCI to determine the RWC for other species that have different morphologies: i.e., deciduous hardwood tree leaves, coniferous tree needles, sclerophyllous tree leaves, and herbaceous annual dicot leaves. A sensitivity analysis was performed in conjunction with this objective.

For remote sensing applications, methods that use NIR and MIR data may be sufficient to delineate stressed areas from non-stressed areas. Rock et al. (1985; 1986) used the ratio of Thematic Mapper Bands 5 to 4 (1.55–1.65 μm and 0.76–0.90 μm, respectively), which is termed the Moisture Stress Index (MSI), to detect areas of coniferous forest damage [both natural damage from old age and damage possibly caused by acid deposition or air pollution (Vogelmann and Rock, 1986; Defeo et al., 1988)]. Yet, the relationships between MSI and measurements of plant water status have been assessed quantitatively only for *Pinus resinosa* (Westman and Price, 1988). Thus, the second objective of this study was to determine how MSI varies with RWC and Equivalent Water Thickness (EWT, leaf water volume/leaf area) for species with different leaf morphologies.

BACKGROUND

The degree of plant water stress can be ascertained by measuring many different physiological variables including decreased growth, stomatal conductance, leaf water potential, or leaf relative water content (Bradford and Hsiao, 1982). Leaf water potential is a measure of the chemical potential of water and gradients of water potential drive water transport across plant membranes (Nobel, 1983); however, it is not clear how leaf water potential can be remotely sensed. Relative Water Content (RWC) is defined as the water volume of a leaf divided by the maximum water volume, i.e., the volume at full turgor (FT). For any given leaf, there is a one-to-one nonlinear relationship between RWC and leaf water potential that can be quantified using a "pressure–volume curve" (Nobel, 1983). Specific leaf water content (g H_2O/g dry mass) is not a good measure of water stress because it is confounded by plant size and dry matter content (Bradford and Hsiao, 1982).

Vegetation indices using red (R; 0.65–0.70 μm) and NIR wavelengths have been successfully used to infer plant water stress and the subsequent reduction of plant productivity (Wiegand et al., 1972; Thompson and Wehmanen, 1979; Walsh, 1987; Richardson and Everitt, 1987). These vegetation indices are highly correlated with total leaf water mass per ground area (Tucker, 1979). However, NIR/R vegetation indices are physiologically related to canopy chlorophyll content and absorbed photosynthetically active radiation (Asrar et al., 1984; Tucker and Sellers, 1986), so that decreases in plant growth or plant senescence caused by water stress, and not low RWC or leaf water potential, is detected using these indices (Jackson et al., 1983).

As stomatal conductance decreases, there is less latent heat loss from transpiration so that leaf temperature increases, which can be detected using thermal-infrared sensors (Bartholic et al., 1972; Jackson, 1982). Based on this temperature response, the degree of water stress can be quantified by various methods (Idso et al., 1977; Blad et al., 1981; Jackson et al., 1986). Temperature response to suddenly induced water stress is faster than changes in NIR reflectance (Jackson and Ezra, 1985). Methods that combine thermal data with NIR and R data, such as in the Normalized Difference Vegetation Index [NDVI $=(\mathrm{NIR}-\mathrm{R})/(\mathrm{NIR}+\mathrm{R})$], are significant advances for the detection of regional vegetation water stress (Hope, 1988; Nemani and Running, 1989).

Water strongly absorbs in the MIR region (Curcio and Petty, 1951) and is a major factor controlling leaf spectral properties (Gausman et al., 1970; Gates, 1980). MIR reflectance increases with decreasing leaf water content (Rohde and Olson, 1967; Thomas et al., 1971; Carlson et al., 1971; Everitt and Nixon, 1986; Ripple, 1986; Westman and Price, 1988). Thus, use of MIR wavelengths, particularly from 1.55 to 1.75 μm, is suggested for remotely sensing leaf water contents (Tucker, 1980).

To adjust for differences in radiance across the landscape, indices have been developed for analysis of satellite digital data in order to compare one area of a scene to another. One such index is the MSI (Rock et al., 1985; 1986). Hardisky et al. (1983) showed that the Normalized Difference Infrared Index [II = (NIR − MIR)/(NIR + MIR)] is highly correlated with canopy water content (g H_2O/m^2 ground area). Also, the ratio of Thematic Mapper Band 5 to Band 7 (1.55–1.75 μm and 2.08–2.35 μm, respectively) is highly correlated with the water content of soils and vegetation (Elvidge and Lyon, 1985; Musick and Pelletier, 1986, 1988).

The absolute leaf water content per leaf area (volume/area) defines a depth of water spread over the leaf area and is termed the Equivalent Water Thickness (EWT). With advanced leaf spectral models, the EWT of a leaf may be predicted from a single leaf spectrum (Gausman et al., 1970). However, in a subsequent study, Allen et al. (1971) found that the predicted EWT from leaf spectra did not equal the actual leaf EWT.

Hunt et al. (1987) developed the Leaf Water Content Index (LWCI) for remotely sensing RWC. Using the Beer–Lambert–Bouguer law, EWT is calculated by

$$\mathrm{EWT} = -\ln(1-a)/k, \tag{1}$$

where k is the extinction coefficient (m^{-1}) of the leaf at a wavelength of 1.6 μm and a is the leaf absorptance of water equal to $(R^D_{1.6} - R_{1.6})$, the reflectance factors at a wavelength of 1.6 μm for an air-dry leaf and the same leaf while hydrated, respectively. Transmittance was assumed to be negligible; a sensitivity analysis on this assumption is discussed in a subsequent section. RWC is EWT/EWT$^{\mathrm{FT}}$ by definition, so that

$$\mathrm{LWCI} = \frac{-\ln\left[1-\left(R^D_{1.6} - R_{1.6}\right)\right]}{-\ln\left[1-\left(R^D_{1.6} - R^{\mathrm{FT}}_{1.6}\right)\right]}, \tag{2}$$

where $R^{\mathrm{FT}}_{1.6}$ is the reflectance factor at 1.6 μm at full turgor and $(R^D_{1.6} - R^{\mathrm{FT}}_{1.6})$ is the absorptance for the fully hydrated leaf. Thus, LWCI is expected to equal RWC of a given leaf (Hunt et al., 1987).

Two parameters are required for Eq. (2): $R^{\mathrm{FT}}_{1.6}$ and $R^D_{1.6}$. In practice, these parameters can be calculated using Eq. (2) if reflectances are obtained at two known, different RWC (Hunt et al., 1987). One parameter can be eliminated given the assumption that $R^D_{1.6}$ is equal to $R_{0.82}$, which is the reflectance factor at 0.82 μm (Rohde and Olson, 1967; Thomas et al., 1971). Then

$$\mathrm{LWCI} = \frac{-\ln\left[1-\left(R_{0.82} - R_{1.6}\right)\right]}{-\ln\left[1-\left(R_{0.82} - R^{\mathrm{FT}}_{1.6}\right)\right]}, \tag{3}$$

leaving only one parameter $R^{\mathrm{FT}}_{1.6}$ determined from a measured $R_{1.6}$ at a known RWC. The difference, $R_{0.82} - R_{1.6}$, is an estimate of the absorptance of water at a wavelength of 1.6 μm. Equations (2) and (3) were presented in Hunt et al. (1987) as the ratio of base 10 logarithms, which is equivalent to the ratio of Napierian logarithms above.

MATERIALS AND METHODS

Leaves of *Quercus agrifolia* (California live oak), *Picea pungens* (blue spruce), and *Liquidambar styraciflua* (sweetgum) were collected from trees at the Jet Propulsion Laboratory (Pasadena, California), and leaves of *Picea rubens* (red spruce) were collected from trees on Camels Hump Mountain (near Burlington, Vermont). The leaves were placed in plastic bags with moist paper towels, transported in a cool dark container to the laboratory, and stored in a refrigerator until use (within 24 h). Plants of *Glycine max var* Harosoy (soybean) were grown in a controlled environment room (temperature 20°C, relative humidity 50%, photosynthetically active radiation of 500 $\mu mol\,m^{-2}s^{-1}$, photoperiod of 16 h light/8 h dark), where the plants were watered three times a week with a commercial nutrient solution including micronutrients.

The petioles or stems of the leaves selected for use were recut under water and allowed to hydrate to a constant weight, defined as the mass at full turgor (W^{FT}) corresponding to an RWC of 1.0 (100%). Directional-hemispherical reflectance factors were measured using a Beckman UV 5240 spectrometer[1] with a Halon standard for individ-

[1]Mention of trade names does not imply endorsement by NASA, by the Jet Propulsion Laboratory, California Institute of Technology, or by the University of New Hampshire.

ual leaves; needles of both *Picea* species (abbreviated spp.) were stacked in an instrument sample container to about three layers deep for reflectance measurements. The number of leaves sampled was 10 for *Q. agrifolia*, 15 for *L. sytraciflua*, four (containers of needles) for *P. pungens*, and 12 for *G. max*; bidirectional reflectance factors of *P. rubens* ($n = 4$ containers of needles) were measured using a Geophysical Environmental Resources Visible/Infrared Intelligent Spectrometer (VIRIS) with a Corning Fiberfrax standard.

The leaves were placed on a laboratory bench to desiccate slowly. Reflectance spectra were obtained every other hour during the daytime over the next several days until the leaves were air dry. With each spectrum, the leaf (or container) mass (W) was obtained. After the measurements were completed, the leaves were oven dried at 60°C to obtain the dry mass (W^D). RWC was then calculated as $(W - W^D)/W^{FT} - W^D)$. One-sided leaf areas were obtained using a Delta − T Devices area meter. Equivalent Water Thickness (EWT) was defined as the leaf water volume divided by the leaf area (A) and calculated as $(W - W^D)/d_W A$, where d_W is the density of water (1000 kg/m^3). For *Picea* spp., the area of the container was used in place of leaf area. $R_{0.82}$ and $R_{1.6}$ were determined for each spectrum. The data at RWC of 1.0 and RWC near 0.0 were used to determine the parameters for LWCI using either Eqs. (2) or (3), so that these data were not used in the analysis of LWCI versus RWC.

RESULTS AND DISCUSSION

Leaf Water Content Index

As the leaves dried, reflectance factors in both the MIR and NIR increased for *L. styraciflua* (hardwood deciduous tree leaves) and *Q. agrifolia* (sclerophyllous tree leaves; Fig. 1). For *G. max* (herbaceous dicot leaves) and *Picea* spp. (conifer needles), only the reflectance factors in the MIR increased significantly (Fig. 1, data for *P. rubens* not shown). $R_{1.6}$ was about equal to $R_{0.82}$ for dry *G. max* leaves, but not for leaves of *Picea* species, *G. max*, and *Q. agrifolia*. Thus, Eq. (3) was used to calculate LWCI for *G. max*, whereas Eq. (2) was used to calculate LWCI for the other species. The absolute changes in reflectance factors in the visible region were small for all species (Fig. 1).

For all species, the LWCI was about equal to RWC and varied about the 1:1 line, especially for naturally occurring RWC between 0.5 and 1.0 (Fig. 2). The slope and y-intercepts were not significantly different ($P < 0.95$) from 1.0 and 0.0, respectively, for *Picea* spp., *L. styraciflua*, and *Q. agrifolia*; however, the slope and y-intercept were significantly different ($P > 0.95$) from 1.0 and 0.0, respectively, for *G. max* (Table 1). The r^2 for regressions forced to the $y = x$ line was very high for *Q. agrifolia* (0.985), *Picea* species (0.991), and *L. styraciflua* (0.974) showing that LWCI explains most of the variation in the data (Fig. 2). For *G. max*, the r^2 for the forced $y = x$ line was moderately high (0.902) because the least-squares regression line was significantly different from the $y = x$ line (Fig. 2, Table 1).

The LWCI was indeed equal to RWC for the species with different leaf morphologies, except for *G. max*. When RWC was greater than 40% for *G. max*, the slope of a least-squares regression equation was 0.92 [$s.e.$ $(b_1) = 0.064$], which is not significantly different from 1.0 using a t-test, and the y-intercept was 0.074 [$s.e.$ $(b_0) = 0.047$], which is not significantly different from 0.0. Thus, LWCI was also equal to RWC for *G. max* when RWC is greater than 40%, so that the LWCI may be applicable to all species over most of the range of naturally occurring RWC.

Sensitivity Analysis

The sensitivity of LWCI to the assumption of negligible transmittance was determined using a reformulation of Eq. (2):

$$\mathrm{LWCI} = \frac{-\ln\left[1 - f*\left(R_{1.6}^D - R_{1.6}\right)\right]}{-\ln\left[1 - f*\left(R_{1.6}^D - R_{1.6}^{FT}\right)\right]}, \quad (4)$$

where f is a factor that varies from 1.0 when transmittance at a wavelength of 1.6 μm ($T_{1.6}$) is zero, to 2.0 when $T_{1.6} = R_{1.6}$. For various LWCI, which was set equal to RWC, $R_{1.6}$ was calculated using: $f = 1$, $R_{1.6}^D = 0.5$, and $R_{1.6}^{FT} = 0.2$. Then, using the calculated $R_{1.6}$ for the selected RWC (i.e., the selected LWCI when f is 1.0), f was varied from 1.25 to 2.0 to calculate a new LWCI using Eq. (4).

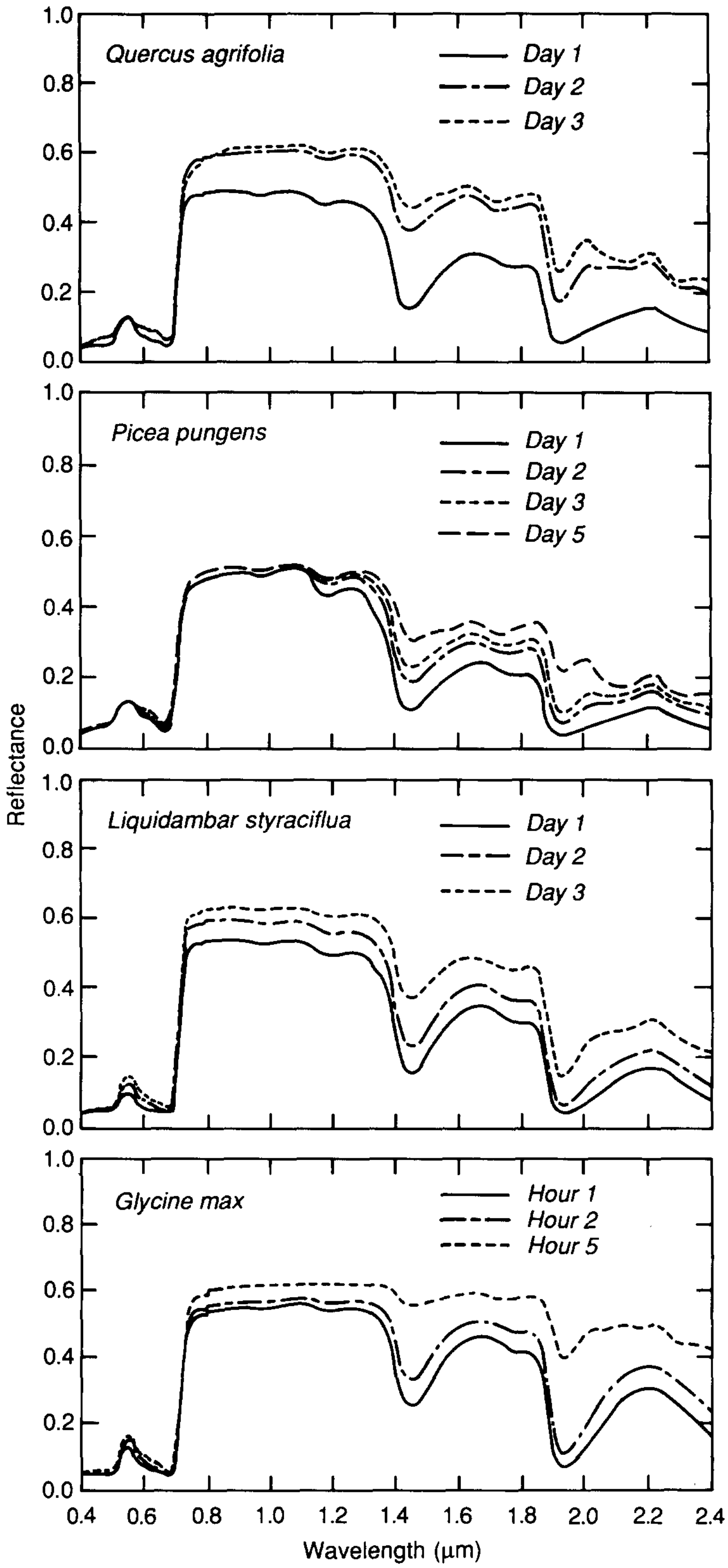

Figure 1. Typical changes of leaf reflectance for a single leaf of: *Quercus agrifolia*, *Picea pungens*, *Liquidambar styraciflua*, and *Glycine max* during drying from Relative Water Contents (RWC) from 1.0 to about 0.2. Rate of drying for the various species is indicated by the time each reflectance spectrum was obtained.

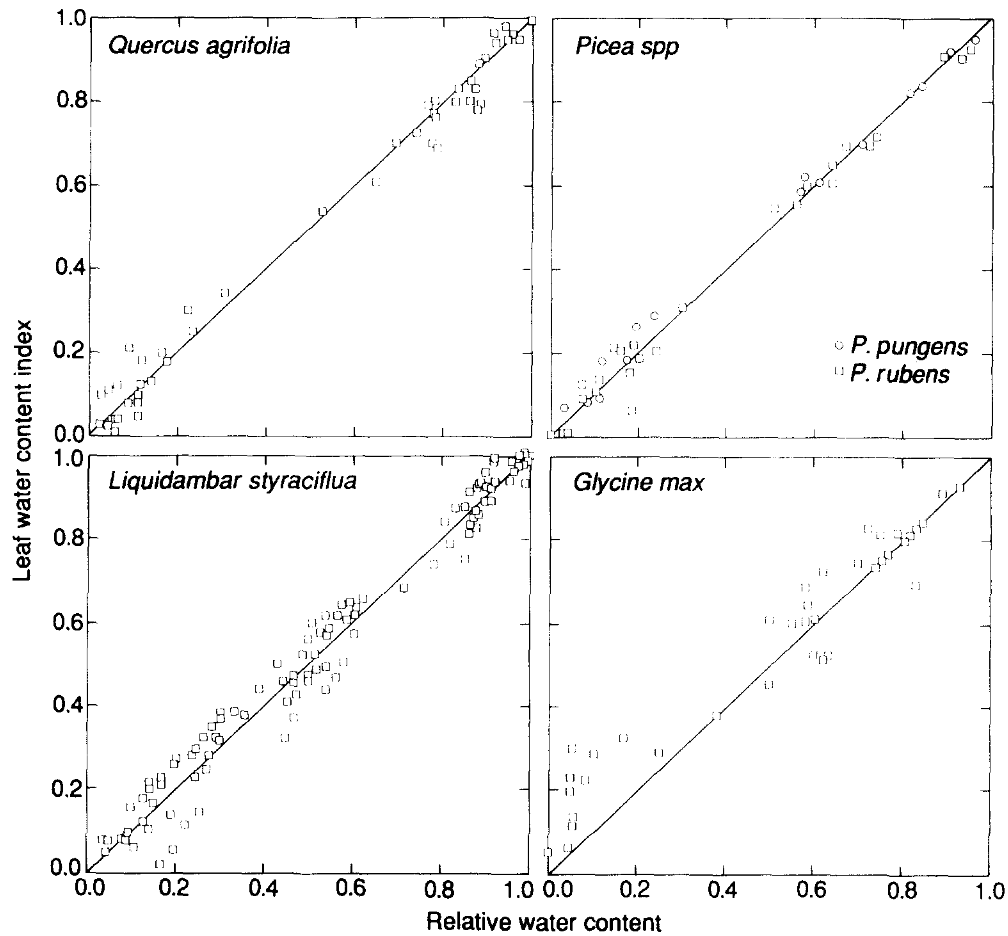

Figure 2. Comparison of calculated Leaf Water Content Index (LWCI) with measured Relative Water Content (RWC) for *Q. agrifolia*, *P. rubens*, *P. pungens*, *L. styraciflua*, and *G. max*. The data for the two *Picea* species (spp) were combined. The lines are $y = x$, and not a least-squares regression line. The statistics for the least-squares regression equations are in Table 1.

The results of this sensitivity analysis show the maximum difference in LWCI between $f = 1.0$ and $f = 2.0$ was 0.054 at an RWC of 0.5 (Fig. 3). Similarly, when f is 2.0 and $R_{1.6}$ is calculated for a given RWC using Eq. (4) and a new LWCI is calculated from the resulting $R_{1.6}$ using Eq. (4) with $f = 1.0$, the maximum difference in LWCI between $f = 2.0$ and $f = 1.0$ was 0.069. These two maximum differences are the same order of magnitude as the standard errors of the estimate (s_{yx}) for the regression lines in Table 1. Although transmittance is considerable for most leaves (Gausman

Table 1. Coefficients and Statistics of a Least-Squares Linear Regression LWCI = $b_0 + b_1 *$RWC for Five Species.[a]

Species	*n*	b_0	$se(b_0)$	b_1	$se(b_1)$	s_{yx}	r^2
Q. agrifolia	49	0.017	0.012	0.97	0.018	0.047	0.98
L. styraciflua	111	−0.004	0.064	1.01	0.015	0.050	0.98
G. max	37	0.13[b]	0.025	0.84[c]	0.041	0.076	0.93
P. pungens	31	0.017	0.008	0.98	0.015	0.026	0.99
P. rubens	18	0.020	0.010	0.99	0.013	0.028	0.99
Picea spp	49	0.018	0.042	0.98	0.013	0.027	0.99

[a]Other symbols are n for the number of points, r^2 for the coefficient of determination, s_{yx} for the standard error of y-estimate, $se(b_0)$ for the standard error of the y-intercept, and $se(b_1)$ for the standard error of the slope.
[b]Significantly different from 0.0 at $P > 0.95$ using a t-test.
[c]Significantly different from 1.0 at $P > 0.95$ using a t-test.

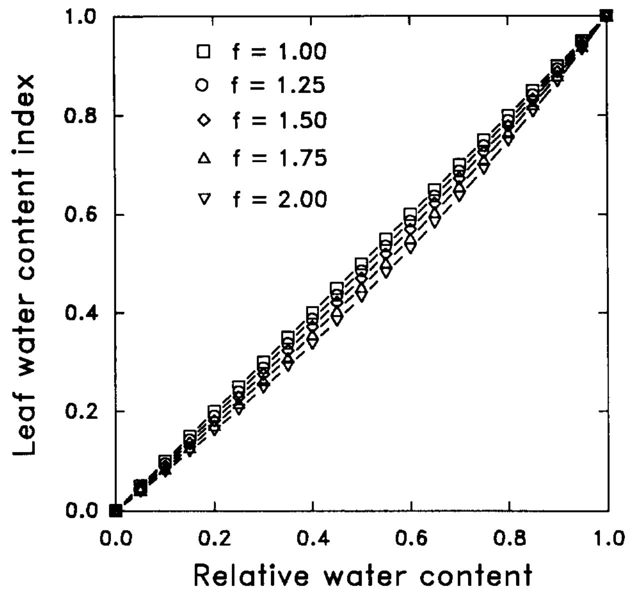

Figure 3. Sensitivity of the Leaf Water Content Index to the assumption of negligible transmittance using Eq. (4). The factor f indicates the amount of transmittance at 1.6 μm wavelength ($T_{1.6}$): $f=1.0$ for $T_{1.6}=0.0$; $f=1.25$ for $T_{1.6}=0.25*R_{1.6}$; $f=1.5$ for $T_{1.6}=0.5*R_{1.6}$; $f=1.75$ for $T_{1.6}=0.75*R_{1.6}$; and $f=2.0$ for $T_{1.6}=R_{1.6}$.

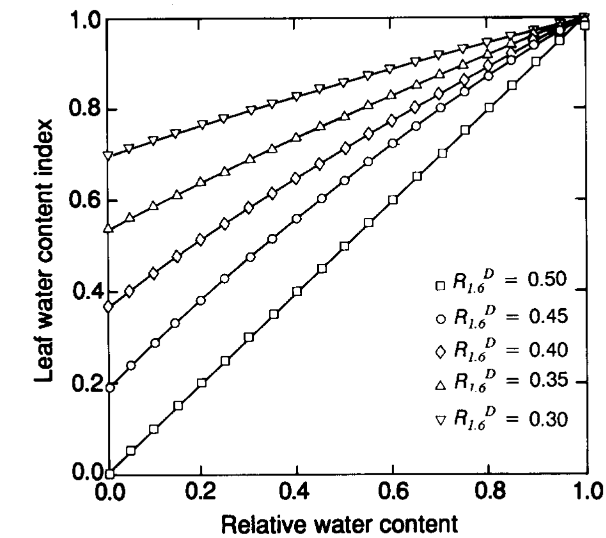

Figure 4. Sensitivity of Leaf Water Content Index to the assumption that $R_{1.6}^D = R_{0.82}$. For various RWC, $R_{1.6}$ was calculated using Eq. (2) for $R_{1.6}^D$ from 0.50 to 0.30 with $R_{1.6}^{FT} = 0.20$. Then, LWCI was calculated using Eq. (3) with $R_{0.82} = 0.50$.

and Allen, 1973; Gates, 1980), the assumption of negligible transmittance does not have a large effect on the prediction of RWC from LWCI using Eq. (2).

Sensitivity of the LWCI to the assumption that $R_{1.6}^D = R_{0.82}$ [Eq. (3)] was assessed by choosing $R_{1.6}^{FT} = 0.2$, varying $R_{1.6}^D$ from 0.5 to 0.3, and calculating $R_{1.6}$ for a given LWCI (which was set equal to RWC) according to Eq. (2). Then, the calculated $R_{1.6}$ and $R_{1.6}^{FT} = 0.2$ were used in Eq. (3) with $R_{0.82} = 0.50$ to obtain a new LWCI for each RWC [i.e., the given LWCI from Eq. (2)].

The sensitivity analysis showed that the assumption of $R_{1.6}^D$ equal to $R_{0.82}$ was poor (Fig. 4). Hence, this assumption, which is necessary to eliminate one parameter, cannot be used to accurately predict RWC from Eq. (3). LWCI from Eq. (3) was used to predict RWC of *G. max*, and the errors at low RWC are similar to the errors in this assumption; but LWCI using Eq. (2) was similar to LWCI using Eq. (3) for *G. max* (data not shown) so that the lack of fit to the 1:1 line was not due to the use of Eq. (3). Whereas determination of one parameter for LWCI at known RWC may be feasible, determination of two parameters at known RWC would be difficult for any practical application in remote sensing. Thus, it is unlikely that the LWCI can be applied to field situations, and the only foreseeable use of the LWCI would be in the laboratory where conditions can be controlled.

Moisture Stress Index

MSI (calculated as $R_{1.6}/R_{0.82}$) was linearly correlated to RWC for leaves of all species: *A. deserti* (data from Hunt et al., 1987), *Picea* spp, *L. styraciflua*, *Q. agrifolia*, and *G. max* (Fig. 5). The r^2 for the linear regression equations (Table 2) were less than the r^2 for the least-squares regression equations of LWCI to RWC (Table 1). The negative slopes for the linear regression lines increased and the y-intercepts decreased with increasing maximum leaf EWT (Table 2). Thus, every species may have its own unique relationship of MSI to RWC.

Furthermore, the relationship between maximum EWT and the regression coefficients (Table 2) suggested that the MSI may be related to EWT. Indeed, MSI was linearly correlated to $\log_{10}$ EWT with an r^2 of 0.889 (Fig. 6). The data for the different species fell along the same line, even though the data were plotted arbitrarily on a $\log_{10}$ scale to accommodate the 4 orders of magnitude difference in EWT from fully hydrated *A. deserti* leaves to air-dry soybean leaves (Fig. 6). The Normalized Difference Infrared Index

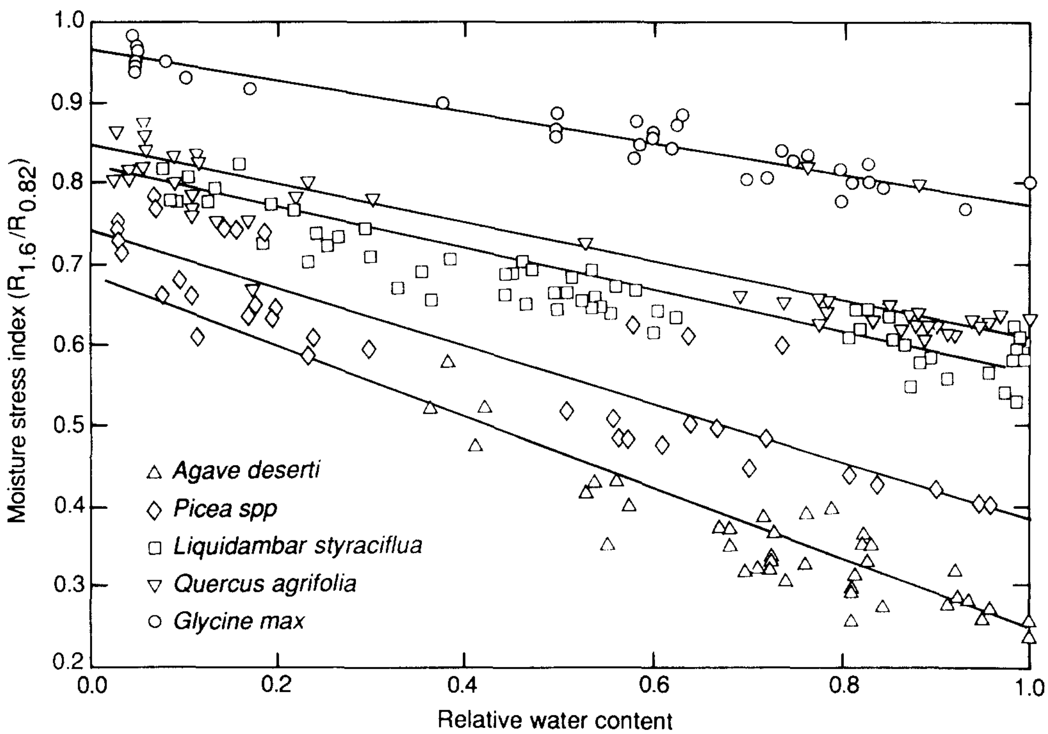

Figure 5. Relationships of the Moisture Stress Index (MSI) to Relative Water Content for *Agave deserti*, *Q. agrifolia*, *P. pungens*, *P. rubens*, *L. styraciflua*, and *G. max*. Data for *A. deserti* were from Hunt et al. (1987). Regression equations and statistics are in Table 2.

[II $= (R_{0.82} - R_{1.6})/R_{0.82} + R_{1.6}$) (Hardisky et al., 1983)] was near-linearly correlated to $\log_{10}$ EWT ($r^2 = 0.818$).

To determine the relationship between EWT and MSI, $R^D_{1.6}$ was assumed to equal $R_{0.82}$, and two sets of leaf parameters were chosen: EWT^{FT} of 1 mm and $R_{0.82} = 0.95$ (appropriate for a succulent leaf), and EWT^{FT} of 0.35 mm and $R_{0.82} = 0.5$ (appropriate for a deciduous tree leaf). $R_{1.6}$ and EWT were then calculated for various RWC by solving

$$\begin{aligned} \mathrm{EWT} &= \mathrm{RWC} * \mathrm{EWT}^{\mathrm{FT}} \\ &= -\ln[1-(R_{0.82}-R_{1.6})]/k, \end{aligned} \tag{5}$$

where k was taken to be 600 m^{-1}, which is that of pure water at 1.6 μm (Curcio and Petty, 1951). The derived MSI was determined from the calculated $R_{1.6}$ and chosen $R_{0.82}$.

The derived MSI for a single leaf increased rapidly then leveled off as the EWT decreased (Fig. 7). This relationship is the result of MSI being linearly correlated to RWC (Fig. 5) and then being plotted on a log scale. Yet, the relationship between the derived MSI and EWT for a single leaf was generally contained in the bounds of the 95% confidence interval of the linear regression equation. Thus, the regression lines in Figures 6

Table 2. Coefficients and Statistics of a Least-Squares Linear Regression, MSI $= b_0 + b_1 *$RWC for Six Species.[a]

Species	*n*	b_0	$se(b_0)$	b_1	$se(b_1)$	s_{yx}	r^2	EWT_m
Q. agrifolia	49	0.83	0.011	−0.20	0.017	0.044	0.75	0.24
L. styraciflua	111	0.81	0.006	−0.23	0.014	0.045	0.72	0.21
G. max	37	0.97	0.006	−0.19	0.010	0.018	0.92	0.09
P. pungens	31	0.76	0.015	−0.33	0.031	0.052	0.80	0.52
P. rubens	18	0.71	0.010	−0.34	0.019	0.029	0.95	1.2
Picea spp	49	0.74	0.032	−0.34	0.024	0.053	0.81	1.2
A. deserti	50	0.71	0.026	−0.46	0.033	0.046	0.80	6.5

[a] The data are for *Agave deserti* from (Hunt et al., 1987). EWT$_m$ is maximum equivalent water thickness (mm); other symbols are defined in Table 1.

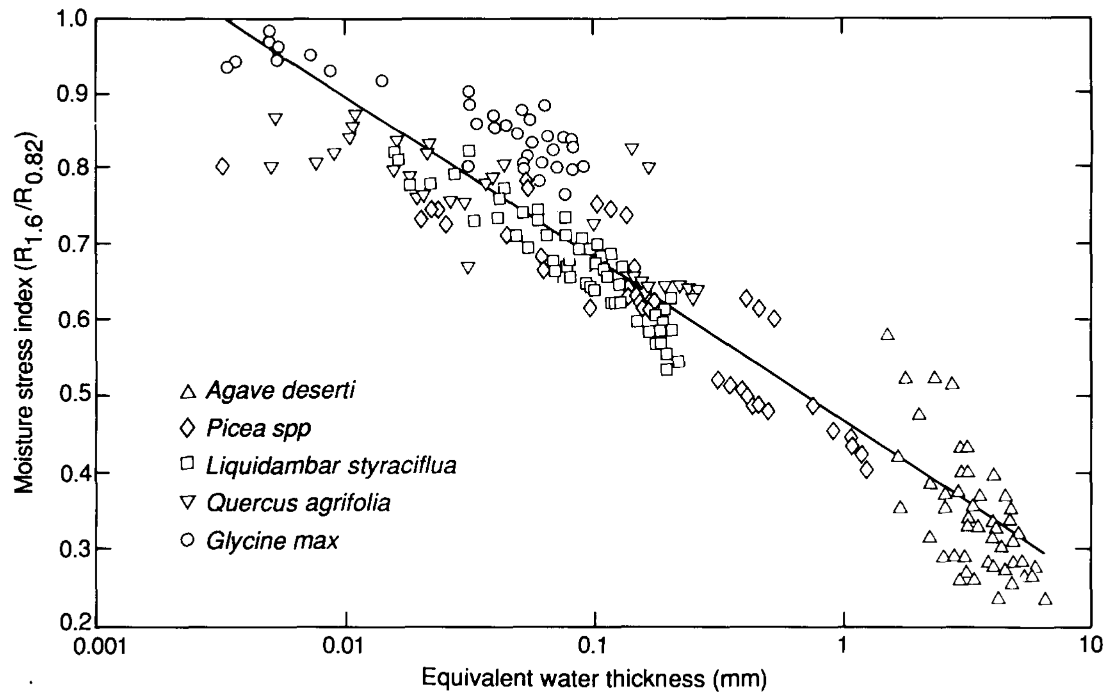

Figure 6. Relationship of the Moisture Stress Index (MSI) to Equivalent Water Thickness (EWT) for all species. EWT is the water volume per projected leaf area. The solid line is the regression equation: $MSI = 0.468 - 0.213 \log_{10} EWT$, n is 296, $r^2 = 0.889$, s_{yx} is 0.0610, $se(b_1)$ is 0.00485, and $se(b_0)$ is 0.00544.

and 7 resulted from the combined nonlinear individual-leaf relationships of MSI to EWT for a large number of leaves.

These results suggest a reason why MSI and other shortwave-infrared vegetation indices are correlated with leaf area index (Hardisky et al., 1983; Gardner et al., 1985; Curran and Williamson, 1987; Peterson et al., 1987). Leaf area index may be thought of as an equal number of stacked leaves (so a leaf area index of 3 equals three layers of leaves, as was the case for *Picea* spp). If the EWT of each leaf adds to the total EWT of the stack, then MSI for the total EWT will be correlated to the number of leaves in the stack, and thus to leaf area index. Moreover, NIR/R vegetation indices are correlated to canopy water content because these vegetation indices are also correlated to LAI (Tucker, 1979).

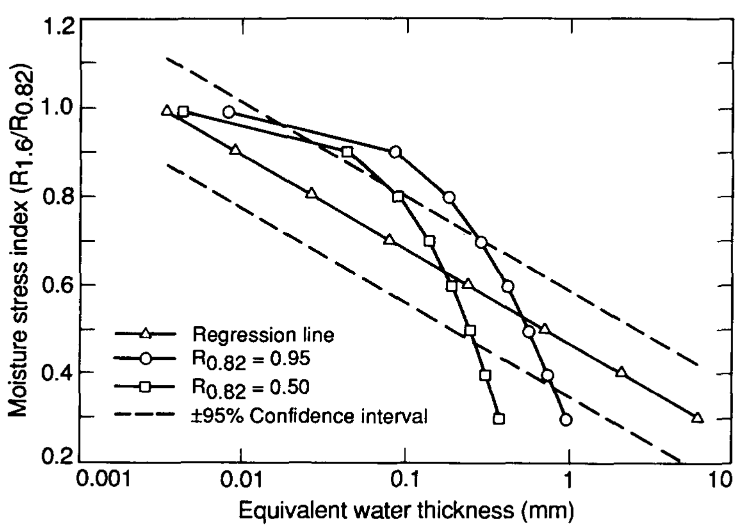

Figure 7. Comparison of Moisture Stress Index (MSI) between the regression equation (±95% confidence interval for prediction of MSI; Fig. 6) and MSI calculated using Eq. (5) for various equivalent water thicknesses. Two leaf morphologies for the calculated MSI were used, a succulent leaf and a deciduous hardwood tree leaf.

If the linear regression equation for MSI versus EWT (Fig. 5) is applicable to plant canopies, then the minimum significant change in EWT detectable by MSI may be calculated. If leaf area index remains constant, then the change EWT_1-EWT_2 is related to the change in RWC times EWT_1. So by subtracting the linear regression equation for Time 2 [Eq. (6b)] from the equation for Time 1 [Eq. (6a)] to get Eq. (6c):

$$MSI_1 = 0.468 - 0.213\log_{10}(EWT_1), \quad (6a)$$

$$-MSI_2 = -0.468 + 0.213\log_{10}(\Delta RWC * EWT), \quad (6b)$$

$$\Delta MSI = 0.213\log_{10}(\Delta RWC), \quad (6c)$$

where $\log_{10}(\Delta RWC * EWT_1)$ is equal to $\log_{10}(\Delta RWC) + \log_{10}(EWT_1)$. The standard error of the estimate for the regression line in Figure 6 is 0.061. Setting ΔMSI equal to -0.061 (because the slope is negative) in Eq. (6c), the minimum detectable change in RWC is 52%. Because this change is independent of initial EWT, a fully hydrated canopy must lose about one-half of its water (RWC of $1 - 0.52 = 0.48$) before a significant difference in MSI caused by water stress can be remotely sensed.

There are three broad categories of ways plants deal with drought (Turner, 1979): 1) drought escape typical of a plant that completes its life cycle before the onset of drought; 2) maintenance of high leaf water content by reducing transpiration and increasing root water uptake; and 3) tolerance of low leaf water contents by cellular adjustment. Of these three categories, remotely sensed MSI may detect plant water stress for only those plants in the third category that tolerate low leaf water contents. For example, evergreen shrubs in the Californian chaparral can withstand leaf RWC of 0.5 (water potentials of -5.0 MPa) and survive until the next wet season (Bowman and Roberts, 1985; E. R. Hunt, Jr. and P. J. Riggan, unpublished data).

Relative water contents for stressed plants in the first two categories are about 0.8–0.7 (Running, 1980). If RWC greater than 0.5 cannot be reliably determined using the MSI, then water stress cannot be detected for these plants until the leaves are senescent from lack of water. Moreover, since RWC of 0.5 represents extreme water stress for those plants that tolerate low water contents, MSI may not be able to detect the incipient stages of water stress for any vegetation type.

MSI does detect something unique about coniferous forest damage that cannot be detected using NIR/R vegetation indices (Rock et al., 1985; 1986; Vogelmann and Rock, 1986; Defeo et al., 1988); hence, it is unlikely that the differences in MSI between damaged and undamaged stands are related to differences in leaf area index. Although forest damage from air pollution and acid deposition may be related to water stress (E. R. Hunt, Jr., B. N. Rock, J. E. Vogelmann, and A. F. Vogelmann, unpublished data), this and other studies (Pierce et al., 1990; Riggs and Running, 1989) show that possible water stress cannot be the reason for the ability of the MSI to detect forest damage. Thus, the physiological and ecological bases for various vegetation indices are not yet understood.

CONCLUSIONS

The LWCI from Eq. (2) was an accurate estimator of RWC for species with different leaf morphologies: succulents (from Hunt et al., 1987), sclerophyllous trees (*Q. agrifolia*), conifers (*Picea* species), hardwood deciduous trees (*L. styraciflua*), and herbaceous dicot annuals (*G. max*). Therefore, LWCI is an index that measures leaf RWC directly and can be used to determine when certain plants are water stressed. However, the required reflectances at two different and known RWC make the LWCI practical only in a laboratory, and impractical for field applications.

MSI ($R_{1.6}/R_{0.82}$) is correlated to the depth of liquid water in a leaf and possibly in a canopy. Since EWT is correlated to leaf area index, MSI should be correlated to leaf area index. MSI was not sensitive enough to determine changes in EWT that occur for water-stressed canopies at constant leaf area index, because large changes in RWC must occur before water stress can be reliably detected.

Thus, it is unlikely that plant water stress can be detected from satellites using NIR and MIR wavelengths. A similar conclusion has been reached by Pierce et al. (1990) for field-stressed conifers using the NS-001 Thematic Mapper Simulator and by Riggs and Running (1989) over the same sites using the Airborne Imaging Spectrometer (AIS). So, thermal-infrared bands, with or without companion vegetation indices, may be the only practical method for detection of water stress over large areas.

We thank: Timari Wilson and Sam K. S. Wong for assistance in obtaining the leaf spectral measurements; Dr. James E. Vogelmann, Dr. Jack F. Paris, Lars L. Pierce, George A. Riggs, and Dr. Steven W. Running for valuable discussions; Dr. R. L. Bernard (Department of Agronomy, University of Illinois) for providing the Harosoy soybean seeds; and three anonymous reviewers for suggestions which improved the manuscript. E. R. Hunt was funded by the NASA Land Processes Branch, Terrestrial Ecosystems Program. The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES

Allen, W. A., Gausman, H. W., Richardson, A. J., and Cardenas, R. (1971), Water and air changes in grapefruit, corn, and cotton leaves with maturation, *Agron. J.* 63:392–394.

Asrar, G., Fuchs, M., Kanemasu, E. T., and Hatfield, J. L. (1984), Estimating absorbed photosynthetic radiation and leaf area index from spectral reflectance in wheat, *Agron. J.* 76:300–306.

Bartholic, J. F., Namken, L. N., and Wiegand, C. L. (1972), Aerial thermal scanner to determine temperatures of soils and of crop canopies differing in water stress, *Agron. J.* 64:603–608.

Bauer, M. E., Daughtry, C. S. T., Biehl, L. L., Kanemasu, E. T., and Hall, F. G. (1986), Field spectroscopy of agricultural crops, *IEEE Trans. Geosci. Remote Sens.* GE-24:65–75.

Blad, B. L., Gardner, R. R., Watts, D. G., and Rosenberg, N. J. (1981), Remote sensing of crop water status, *Remote Sens. Quart.* 3:4–20.

Bowman, W. D., and Roberts, S. W. (1985), Seasonal and diurnal water relations adjustments in three evergreen chaparral shrubs, *Ecology* 66:738–742.

Bradford, K. J., and Hsiao, T. C. (1982), Physiological responses to moderate water stress, in *Encyclopedia of Plant Physiology, Vol. 12B: Physiological Plant Ecology II, Water Relations and Carbon Assimilation* (O. L. Lange, P. S. Nobel, C. B. Osmond, and H. Ziegler, Eds.), Springer-Verlag, New York, Heidelberg, Berlin, pp. 263–324.

Carlson, R. E., Yarger, D. N., and Shaw, R. H. (1971), Factors affecting the spectral properties of leaves with special emphasis on leaf water status, *Agron. J.* 63:486–489.

Curcio, J. A., and Petty, C. C. (1951), The near infrared absorption spectrum of liquid water, *J. Opt. Soc. Am.* 41:302–304.

Curran, P. J., and Williamson, H. D. (1987), GLAI estimation using measurements of red, near infrared, and middle infrared radiance, *Photogramm. Eng. Remote Sens.* 53:181–186.

Defeo, N. J., Rock, B. N., and Vogelmann, J. E. (1988), Detection of forest damage on Whiteface mountain, New York, using Landsat Thematic Mapper data, in *Proc. 21st Symp. Remote Sens. Environ.*, Environmental Research Institute of Michigan, Ann Arbor, MI, pp. 835–842.

Elvidge, C. D., and Lyon, R. J. P. (1985), Estimation of the vegetation contribution to the 1.65/2.22 μm ratio in airborne thematic-mapper imagery of the Virginia Range, Nevada, *Int. J. Remote Sens.* 6:75–88.

Everitt, J. H., and Nixon, J. R. (1986), Canopy reflectance of two drought-stressed shrubs, *Photogramm. Eng. Remote Sens.* 52:1189–1192.

Gardner, B. R., Blad, B. L., Thompson, D. R., and Henderson, K. E. (1985), Evaluation and interpretation of thematic mapper ratios in equations for estimating corn growth parameters, *Remote Sens. Environ.* 18:225–234.

Gates, D. M. (1980), *Biophysical Ecology*, Springer-Verlag, New York, Heidelberg, Berlin.

Gausman, H. W., and Allen, W. A. (1973), Optical parameters of leaves of 30 plant species, *Plant Physiol.* 52:57–62.

Gausman, H. W., Allen, W. A., Cardenas, R., and Richardson, A. J. (1970), Relation of light reflectance to histological and physical evaluations of cotton leaf maturity, *App. Opt.* 9:545–552.

Hardisky, M. A., Klemas, V., and Smart, R. M. (1983), The influence of soil salinity, growth form, and leaf moisture on the spectral reflectance of *Spartina alterniflora* canopies, *Photogramm. Eng. Remote Sens.* 49:77–83.

Hope, A. S. (1988), Estimation of wheat canopy resistance using combined remotely sensed spectral reflectance and thermal observations, *Remote Sens. Environ.* 24:369–383.

Hunt, E. R., Jr., Rock, B. N., and Nobel, P. S. (1987), Measurement of leaf relative water content by infrared reflectance, *Remote Sens. Environ.* 22:429–435.

Idso, S. B., Jackson, R. D., and Reginato, R. J. (1977), Remote sensing of crop yields, *Science* 196:19–25.

Jackson, R. D. (1982), Canopy temperature and crop water stress, *Adv. Irrig.* 1:45–85.

Jackson, R. D., and Ezra, C. E. (1985), Spectral response of cotton to suddenly induced water stress, *Int. J. Remote Sens.* 6:177–185.

Jackson, R. D., Slater, P. N., and Pinter, P. J., Jr. (1983), Discrimination of growth and water stress in wheat by various vegetation indices through clear and turbid atmospheres, *Remote Sens. Environ.* 13:187–208.

Jackson, R. D., Pinter, P. J., Jr., Reginato, R. J., and Idso, S. B. (1986), Detection and evaluation of plant stresses for crop management decisions, *IEEE Trans. Geosci. Remote Sens.* GE-24:99–106.

Musick, H. B., and Pelletier, R. E. (1986), Response of some thematic mapper band ratios to variation in soil water content, *Photogramm. Eng. Remote Sens.* 52:1661–1668.

Musick, H. B., and Pelletier, R. E. (1988), Response to soil moisture of spectral indexes derived from bidirectional reflectance in thematic mapper wavebands, *Remote Sens. Environ.* 25:167–184.

Nemani, R. R., and Running, S. W. (1989), Estimation of regional surface resistance to evapotranspiration from NDVI and thermal-IR AVHRR data, *J. Appl. Meteorol.* 28:276–284.

Nobel, P. S. (1983), *Biophysical Plant Physiology and Ecology*, Freeman, San Francisco.

Peterson, D. L., Spanner, M. A., Running, S. W., and Teuber, K. B. (1987), Relationship of thematic mapper simulator data to leaf area index of temperate coniferous forests, *Remote Sens. Environ.* 22:323–341.

Pierce, L. L., Riggs, G. A., and Running, S. W. (1990), Remote detection of canopy water stress in coniferous forests using the NS-001 Thematic Mapper Simulator and the Thermal Infrared Multispectral Scanner, *Photogramm. Eng. Remote Sens.*, in press.

Richardson, A. J., and Everitt, J. H. (1987), Monitoring water stress in buffelgrass using hand-held radiometers, *Int. J. Remote Sens.* 8:1797–1806.

Riggs, G. A., and Running, S. W., (1989), Detection of canopy water stress in conifers using the Airborne Imaging Spectrometer (AIS), *Remote Sens. Environ.*, in press.

Ripple, W. P. (1986), Spectral reflectance relationships to leaf water stress, *Photogramm. Eng. Remote Sens.* 52: 1669–1675.

Rock, B. N., Williams, D. L., and Vogelmann, J. E. (1985), Field and airborne spectral characterization of suspected acid deposition damage in red spruce (*Picea rubens*) from Vermont, in *1985 Machine Processing of Remotely Sensed Data Symposium*, Purdue University, Lafayette, IN, pp. 71–81.

Rock, B. N., Vogelmann, J. E., Williams, D. L., Vogelmann, A. F., and Hoshizaki, T. (1986), Remote detection of forest damage, *Bioscience* 36:439–445.

Rohde, W. G., and Olson, C. E., Jr. (1967), Estimating leaf moisture content from infrared reflectance data, in *Third Biennial Workshop on Color Aerial Photography in the Plant Sciences*, American Society of Photogrammetry, Falls Church, VA, pp. 144–164.

Running, S. W. (1980), Relating plant capacitance to the water relations of *Pinus contorta*, *For. Ecol. Manage.* 2:237–252.

Thomas, J. R., Namken, L. N., Oerther, G. F., and Brown, R. G. (1971), Estimating leaf water content by reflectance measurements, *Agron. J.* 63:845–847.

Thompson, D. R., and Wehmanen, O. A. (1979), Using Landsat digital data to detect moisture stress, *Photogramm. Eng. Remote Sens.* 45:201–207.

Tucker, C. J. (1979), Red and photographic infrared linear combinations for monitoring vegetation, *Remote Sens. Environ.* 8:127–150.

Tucker, C. J. (1980), Remote sensing of leaf water content in the near infrared, *Remote Sens. Environ.* 10:23–32.

Tucker, C. J., and Sellers, P. J. (1986), Satellite remote sensing of primary production, *Int. J. Remote Sens.* 7:1395–1416.

Turner, N. C. (1979), Drought resistance and adaptations to water deficits in crop plants, in *Stress Physiology of Crop Plants*, (C. H. Mussell and R. C. Staples, Eds.), Wiley, New York, pp. 343–372.

Vogelmann, J. E., and Rock, B. N. (1986), Assessing forest decline in coniferous forests of Vermont using NS-001 Thematic Mapper Simulator data, *Int. J. Remote Sens.* 7:1303–1321.

Walsh, S. J. (1987), Comparison of NOAA AVHRR data to meteorologic drought indices, *Photogramm. Eng. Remote Sens.* 53:1069–1074.

Westman, W. E., and Price, C. V. (1988), Spectral changes in conifers subjected to air pollution and water stress: experimental studies, *IEEE Trans. Geosci. Remote Sens.* GE-24:11–21.

Wiegand, C. L., Gausman, H. W., and Allen, W. A. (1972), Physiological factors and optical parameters as bases of vegetation discrimination and stress analysis, in *Proceedings of the Seminar on Operational Remote Sensing*, American Society of Photogrammetry, Falls Church, VA, pp. 82–102.