

Relations of remote sensing leaf water indices to leaf water thickness in cowpea, bean, and sugarbeet plants

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Abstract

Remote sensing leaf water indices depend on two variables: the relative water content (RWC) of leaf cells, which may serve as an indicator for water deficit stress in plants, and leaf thickness. The measurement of leaf water thickness (LWT) appears to be an experimental method that can be well correlated with leaf water indices. We studied how leaf water indices relate to the LWT in cowpea, bean, and sugarbeet. In all three species, the LWT increased linearly with increasing leaf thickness. The T_{1300}/T_{1450} leaf water index, based on light transmitted through leaves, showed a strong exponential correlation with the LWT as expected from theoretical analysis. However, the R_{1300}/R_{1450} leaf water index, based on light reflected from leaves, exhibited a characteristic logarithmic correlation with the LWT. For both leaf water indices we found only minor differences between the three species examined.

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1. Introduction

1.1. Background

The determination of plant water status is a major goal in agricultural and ecological remote sensing applications (Ceccato et al., 2001; Gao & Goetz, 1995; Strachan et al., 2002; Ustin et al., 1998). Of particular interest would be if plant water deficit stress could be detected remotely (Cibula et al., 1992; Jackson et al., 1986; Pearson et al., 1994; Peñuelas et al., 1993; Pierce et al., 1990; Serrano et al., 2000). For such applications, it is safe to use the term “leaf water content” since it implies any type of measurement describing the water status of plants. Also, this term avoids a connection with the expression “water deficit stress”. Specifying exactly how the terms “leaf water content” and “plant water status” relate to remote sensing data, however, is not as trivial. The matter is further complicated by the largely unanswered question of precisely what event or condition defines

the onset of water deficit stress in plants (Jackson et al., 1986; Sinclair & Ludlow, 1985). We focus here on the correlation between remote sensing data and plant water status parameters.

Over the past decades, numerous studies have investigated if remote sensing data, such as dual-wavelength ratios utilizing water absorption features, can be used for the detection of water deficit stress in plants (Allen et al., 1969; Carter, 1994; Downing et al., 1993; Gao, 1996; Gausman, 1974; Holben et al., 1983; Jackson & Ezra, 1985; Jackson et al., 1986; Jacquemoud et al., 1996; Pearson et al., 1994; Roberts et al., 1997; plus references listed in Table 1). Although basic correlations could often be established, practical applicability of such techniques has proven to be a complex task. One reason for this difficult applicability is the typical large data variability evident in many previous studies. Such variability may be due to the possible influences of extraneous variables, such as Sun and sensor view angle, illumination intensity, scene surface heterogeneity, background properties, and atmospheric optical variability (Cohen, 1991; Dawson et al., 1999; Peñuelas et al., 1993). However, earlier studies also used a variety of different parameters to actually describe plant water status, which are summarized in Table 1.

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Table 1
Parameters used to describe the water status of plants

#	Leaf water content parameter	Formulation/method	Unit	References
1	Relative water content	$RWC = (W_F - W_D) / (W_{FT} - W_D) * 100$	%	(Bowman, 1989; Carter, 1991; Cibula et al., 1992; Cohen, 1991; Hunt & Rock, 1989; Knipling, 1970; Peñuelas et al., 1993, 1996; Pierce et al., 1990; Ripple, 1986; Serrano et al., 2000; Thomas et al., 1971; Tucker, 1980; Woolley, 1971)
2	Total water potential	Measured by Scholander pressure chamber	MPa	(Bowman, 1989; Peñuelas et al., 1993, 1996; Pierce et al., 1990; Ripple, 1986)
3	Osmotic water potential	Pressure–volume method	MPa	Peñuelas et al. (1996)
4	Turgor pressure	Pressure–volume method	MPa	Bowman (1989)
5	Plant water concentration (content)	$PWC = ((W_F - W_D) / W_D) * 100$	%	(Peñuelas et al., 1997; Piñol et al., 1998)
6	Leaf hydration or canopy moisture content	$H = (W_F - W_D) / W_D$	$\text{g}_{\text{H}_2\text{O}}/\text{g}_{\text{dry}}$	(Peñuelas et al., 2004; Ustin et al., 1998)
7	% Leaf water content or % canopy water content	$\%LWC = ((W_F - W_D) / W_F) * 100$	%	(Ceccato et al., 2001; Gao & Goetz, 1995; Rollin & Milton, 1998)
8	Leaf water content or canopy water content or specific water density	$LWC = (W_F - W_D) / A$	g/m^2 or scaled	(Ceccato et al., 2002a,b; Danson et al., 1992; Dawson et al., 1999; Sims & Gamon, 2003; Strachan et al., 2002; Ustin et al., 1998)
9	Leaf water thickness or measured EWT	$LWT = (W_F - W_D) / (D_W * A)$	μm	(Allen et al., 1971; Gausman et al., 1970; Hunt & Rock, 1989; Tucker, 1980)

W_F denotes fresh-weight of a leaf sample, W_D denotes dry-weight of a leaf sample, W_{FT} denotes weight-at-full-turgor-pressure of a leaf sample, D_W denotes the density of water, and A denotes the leaf sample-area.

In principle, each of the parameters listed in Table 1 could be used for the assessment of water deficit stress in plants, since each of them changes to a certain extent during the development of water deficit stress (Bowman, 1989; Major & Johnsen, 2001; Morgan, 1995; Peñuelas et al., 2004; Riggs & Running, 1991; Sinclair & Ludlow, 1985). These parameters may also be correlated with remote sensing data qualitatively. However, not only does the variety of parameters used increase the difficulty in comparing the results of these studies, it also raises the question as to which of those parameters, if any, is the true independent variable for such measurements. Correlating remote sensing data erroneously to parameters which in fact are not independent for these measurements may be another explanation for data variability in earlier studies.

1.2. Light reflection within leaves

In order to link cause and effect relationships between plant water status and remote sensing data fruitfully, it is imperative to study how light is reflected from leaves. As early as 1918, Willstätter and Stoll pointed out that most light incident to the adaxial (upper) side of a leaf is not specularly reflected from the leaf surface, but rather typically penetrates the leaf and is reflected from within the leaf (Willstätter & Stoll, 1918: 122–127; Grant, 1987; Grant et al., 1987; Vogelmann et al., 1996). According to the Willstätter and Stoll theory, reflection within the leaf occurs mainly at the layer of spongy mesophyll cells due to the difference of refractive indices between cell walls and intercellular air. Woolley (1971) estimated the contribution of cell wall to air interfaces to leaf reflection by eliminating these interfaces; that is, by replacing intercellular air spaces with liquids of refractive indices higher than air ($m_{\text{air}}=1$). As the refractive indices of these liquids increased, and consequentially the difference between the refractive index of cell walls and these liquids decreased, leaf reflectance decreased. Gausman

(1974) corroborated these findings, demonstrating that leaf reflectance mainly originates from the layer of mesophyll cells.

However, when the refractive index of the induced liquid matched the refractive index of cell walls, reflectance was still as high as about 20%, indicating that sources other than cell wall to air interfaces may substantially contribute to leaf reflectance as well. Grant (1987) cautioned that refractive discontinuities other than air to cell wall interfaces, such as cellulose microfibrils in the cell walls, may contribute to leaf reflection. Kumar and Silva (1973) found excellent agreement in leaf reflectance between their advanced light ray tracing model and experimental data, but only after including the refractive discontinuities of cell sap to cell walls, chloroplasts to cell walls, and cell sap to chloroplasts, in addition to cell wall to air discontinuities, into their model. Sinclair (1968: 61–63, 89–92, 132–135) provided convincing evidence that the pathway of light, upon reaching the internal leaf structure, is altered by any cell wall. According to Sinclair's work, the microfibril structures of cell walls themselves induce diffuse scattering of light even in the absence of intercellular air spaces, i.e. refractive discontinuities, causing leaf reflectance to be partly a function of the thickness and number of cell walls encountered by light on its path through leaves. Sinclair's conclusion would explain why reflectance from the adaxial side is typically much larger than reflectance from the abaxial (lower) side of leaves. Therefore, leaf reflectance may not only originate from the layer of spongy mesophyll cells, but also from the layer of palisade cells.

Consequently, each ray of a light beam incident to a leaf may take a unique path through the tissue. Some rays incident to the adaxial surface may be reflected at the layer of mesophyll cells, thus traveling through some mesophyll cells and through the layer of palisade cells twice, while other rays may be reflected right at the palisade layer, traveling through some palisade cells only. It appears to be impossible to determine an exact path as light travels through leaves. Rather, we are left to work with mean absorption path lengths.

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