

Beyond the Crop Water Stress Index: Applying Biophysical Principles to the Measurement of Canopy Stomatal Conductance

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Introduction

Decreased water uptake closes stomates, which reduces transpiration and increases leaf temperature. The leaf or canopy temperature can thus be used to quantify plant water stress. Multiple methods to measure water stress using canopy temperature have been proposed. Nearly all of them are modifications of a 26-year-old index called the crop water stress index, which is based on empirically-established baselines. Here we propose to abandon this relative index and replace it with measurement of canopy stomatal conductance, a biophysical parameter that does not rely on empirical coefficients derived for specific plants and specific climates.

Theory

The crop water stress index (*CWSI*) was defined by Idso et al. (1981) as:

$$CWSI = \frac{(T_C - T_A) - NWSB}{WSB - NWSB} \quad (1)$$

where $T_C - T_A$ is the canopy to air temperature difference, *NWSB* is the non-water-stressed baseline and is the empirically measured lower limit of $T_C - T_A$ for a well-watered canopy transpiring at the potential rate, and *WSB* is the water-stressed baseline, which is extrapolated from the *NWSB* (the baselines were originally derived as a function of vapor pressure deficit). Jackson et al. (1981) showed that the *NWSB* and *WSB* could be theoretically derived from the energy balance for a canopy and developed a theoretically-based *CWSI*. However, the theoretically-based *CWSI* still requires empirical determination of the canopy stomatal conductance at potential ET.

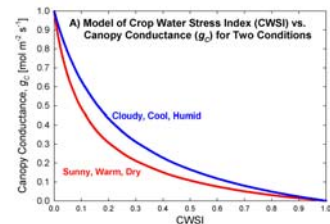
Using the energy balance for a plant canopy, an equation for calculating canopy stomatal conductance (g_c) [mol m⁻² s⁻¹] can be derived:

$$g_c = \frac{g_H P_a [(R_n - G) - g_H C_p (T_C - T_A)]}{g_H \lambda (e_c - e_a) - P_a [(R_n - G) - g_H C_p (T_C - T_A)]} \quad (2)$$

where g_H is boundary layer heat conductance [mol m⁻² s⁻¹], P_a is atmospheric pressure [kPa], R_n is net radiation [W m⁻²], G is soil heat flux [W m⁻²], C_p is specific heat of air [J mol⁻¹ °C⁻¹], λ is latent heat of vaporization [J mol⁻¹], e_c is saturated vapor pressure [kPa] at T_C , e_a is air vapor pressure [kPa].

Application of Eq. (2) to calculate g_c yields a biophysical parameter relating to stomatal aperture, and thus plant water status, rather than a relative index. Calculation of g_c does not require empirical coefficients and includes the same parameters as the theoretically-based *CWSI*, but does not require empirically-determined canopy stomatal conductance at potential ET.

Results



Relationship of canopy stomatal conductance (g_c) and the theoretical crop water stress index (*CWSI*) for the two contrasting climatic conditions (defined in the table at right). Canopy stomatal conductance is more sensitive to incipient water stress than the *CWSI*.

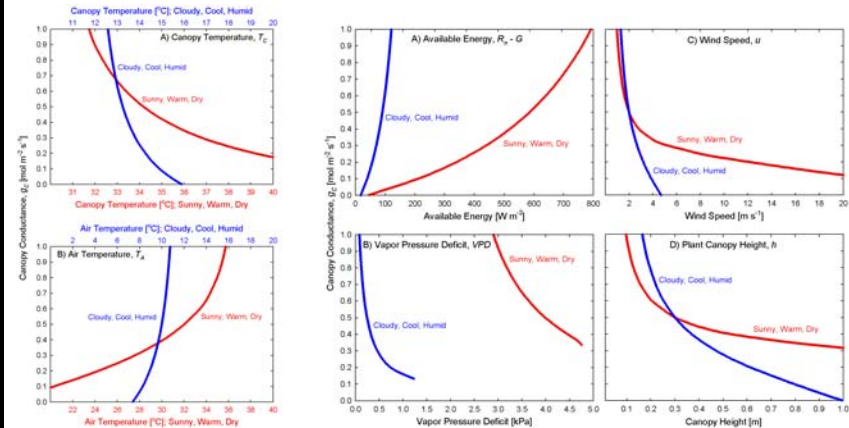


Accurate measurement of canopy temperature is required to determine canopy stomatal conductance (g_c).



Canopy stomatal conductance (g_c) can be calculated by adding a measurement of canopy temperature to a standard ET station.

We performed a sensitivity analysis of g_c using Eq. (2) for both sunny, warm, and dry, and cloudy, cool, and humid conditions (the two conditions are defined in the table below). The measurements required to calculate g_c are T_A , T_C , *VPD*, R_n , G , u , and h . The sensitivity of each parameter was determined by adjusting the parameter in question over a wide range and keeping all others constant (figures below).



Sensitivity of canopy stomatal conductance (g_c) to A) canopy temperature and B) air temperature for two climatic conditions (sunny, warm, and dry; cloudy, cool, and humid). The values of each parameter for the two climatic conditions are given in the table below. A steep slope indicates high sensitivity and a flat slope indicates low sensitivity.

Sensitivity of canopy stomatal conductance (g_c) to A) available energy (net radiation – soil heat flux), B) vapor pressure deficit, C) wind speed, and D) plant canopy height for two climatic conditions (sunny, warm, and dry; cloudy, cool, and humid). The values of each parameter for the two climatic conditions are given in the table below. A steep slope indicates high sensitivity and a flat slope indicates low sensitivity. The g_c plots in B) do not extend to the axes like the others because the vapor pressure deficit range is limited by the conditions listed in the table.

Parameter	Sunny, Warm, Dry	Cloudy, Cool, Humid
Canopy Temperature, T_C [°C]	34.2 ¹	13.3 ¹
Air Temperature, T_A [°C]	32	10
Vapor Pressure Deficit, <i>VPD</i> [kPa]	4.0	0.25
Net Radiation, R_n [W m ⁻²]	650	150
Soil Heat Flux, G [W m ⁻²]	65	15
Wind Speed, u [m s ⁻¹]	2	2
Plant Canopy Height, h [m]	0.3	0.3

Conclusions

- 1 – We propose to abandon the use of the *CWSI*, which is based on empirically-established baselines and reference surfaces, in favor of direct measurement of g_c because g_c is a biophysical parameter that directly relates to stomatal aperture, and thus plant water status, and CO₂ uptake.
- 2 – We derived the equation for calculating g_c in units of mol m⁻² s⁻¹ and compared g_c to the theoretically-based *CWSI* proposed by Jackson et al. (1981).
- 3 – Modeled results show that g_c is much more sensitive to environmental changes under cloudy, cool, and humid conditions versus sunny, warm and dry conditions. This is true for *CWSI* measurements as well.

References

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