

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 27-year-old index called the crop water stress index, which is based on empirically-established baselines. Little work has been done to move from relative and empirically-based stress indices to biophysically-based approaches. Here we demonstrate measurement of canopy stomatal conductance, a biophysical parameter that does not rely on empirical coefficients derived for specific plants and specific climates.

Canopy Stomatal Conductance Model

From the energy balance for a plant canopy, an equation for canopy stomatal conductance (g_C) [$\text{mol m}^{-2} \text{s}^{-1}$] is:

$$g_C = \frac{g_V P_B [(R_n - G - PR) - g_H C_P (T_C - T_A)]}{g_V \lambda (e_{SC} - e_A) - P_B [(R_n - G - PR) - g_H C_P (T_C - T_A)]} \quad (1)$$

where g_V and g_H are boundary layer water vapor and heat conductances [$\text{mol m}^{-2} \text{s}^{-1}$], respectively, P_B is barometric pressure [kPa], R_n is net radiation [W m^{-2}], G is soil heat flux [W m^{-2}], PR is photosynthesis and respiration [W m^{-2}], C_P is specific heat of air [$\text{J mol}^{-1} \text{C}^{-1}$], T_C and T_A are canopy and air temperatures [C], respectively, λ is latent heat of vaporization [J mol^{-1}], e_{SC} is saturated vapor pressure [kPa] at T_C , and e_A is air vapor pressure [kPa].

Equation (1) yields the weighted average stomatal conductance of all leaves in the canopy that contribute to T_C , and is a biophysical parameter relating to stomatal aperture and water status, rather than a relative index. Equation (1) provides a link between prevailing micrometeorological conditions and plant physiological response. The required measurements or estimates necessary to calculate g_C from Eq. (1) are canopy temperature, air temperature, barometric pressure, relative humidity, net radiation, soil heat flux, photosynthesis and respiration, wind speed, and plant canopy height (wind speed and canopy height are necessary for g_V and g_H calculation).

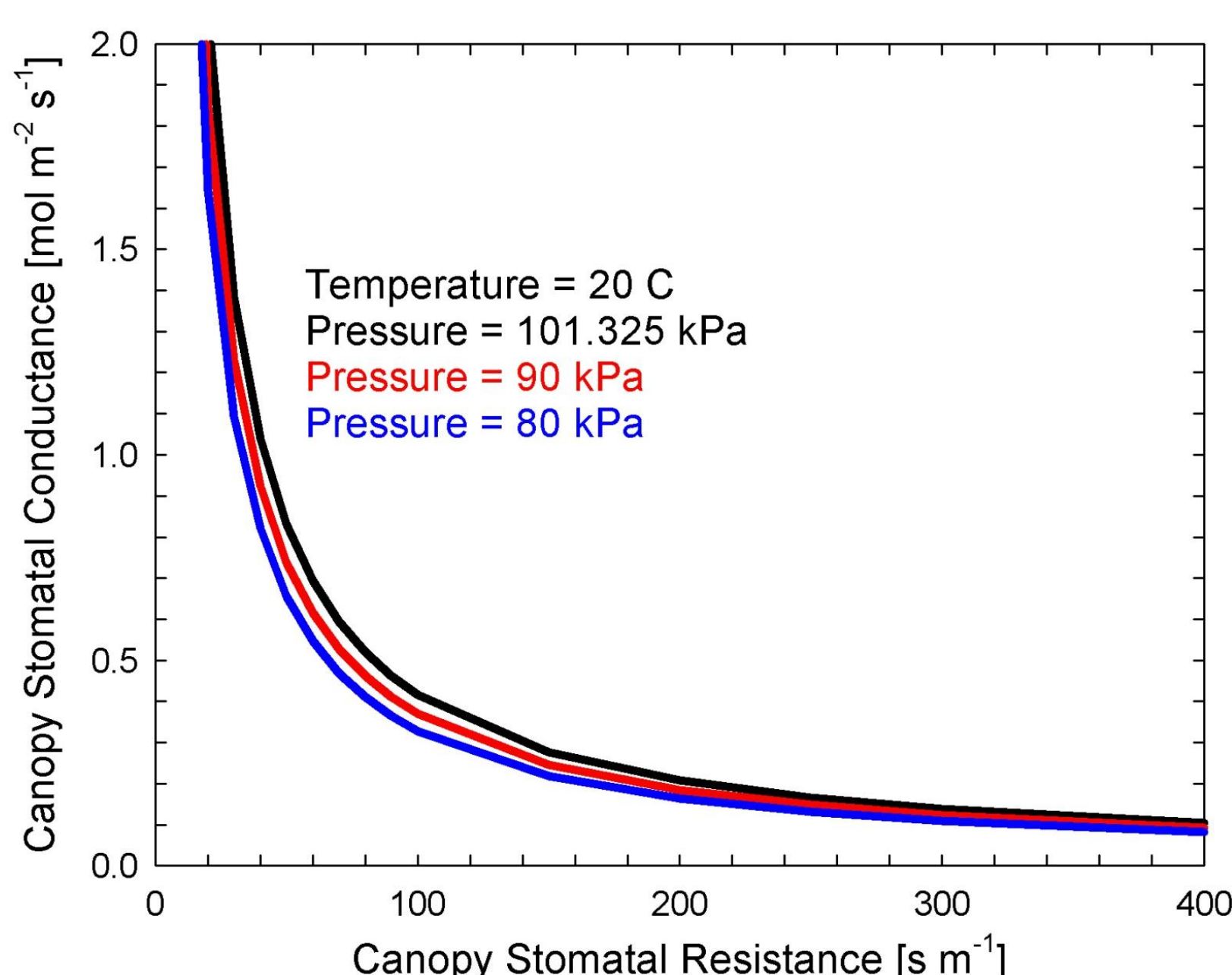
Resistance vs. Conductance

Relationships similar to Eq. (1) have been derived for canopy stomatal resistance (r_C) [s m^{-1}] rather than conductance [$\text{mol m}^{-2} \text{s}^{-1}$] because resistance units are widely used in meteorology. They are related through the molar density of air (ρ_{Mol}) [mol m^{-3}]:

$$g_C = \frac{\rho_{Mol}}{r_C} \quad (2)$$

Advantages of conductance:

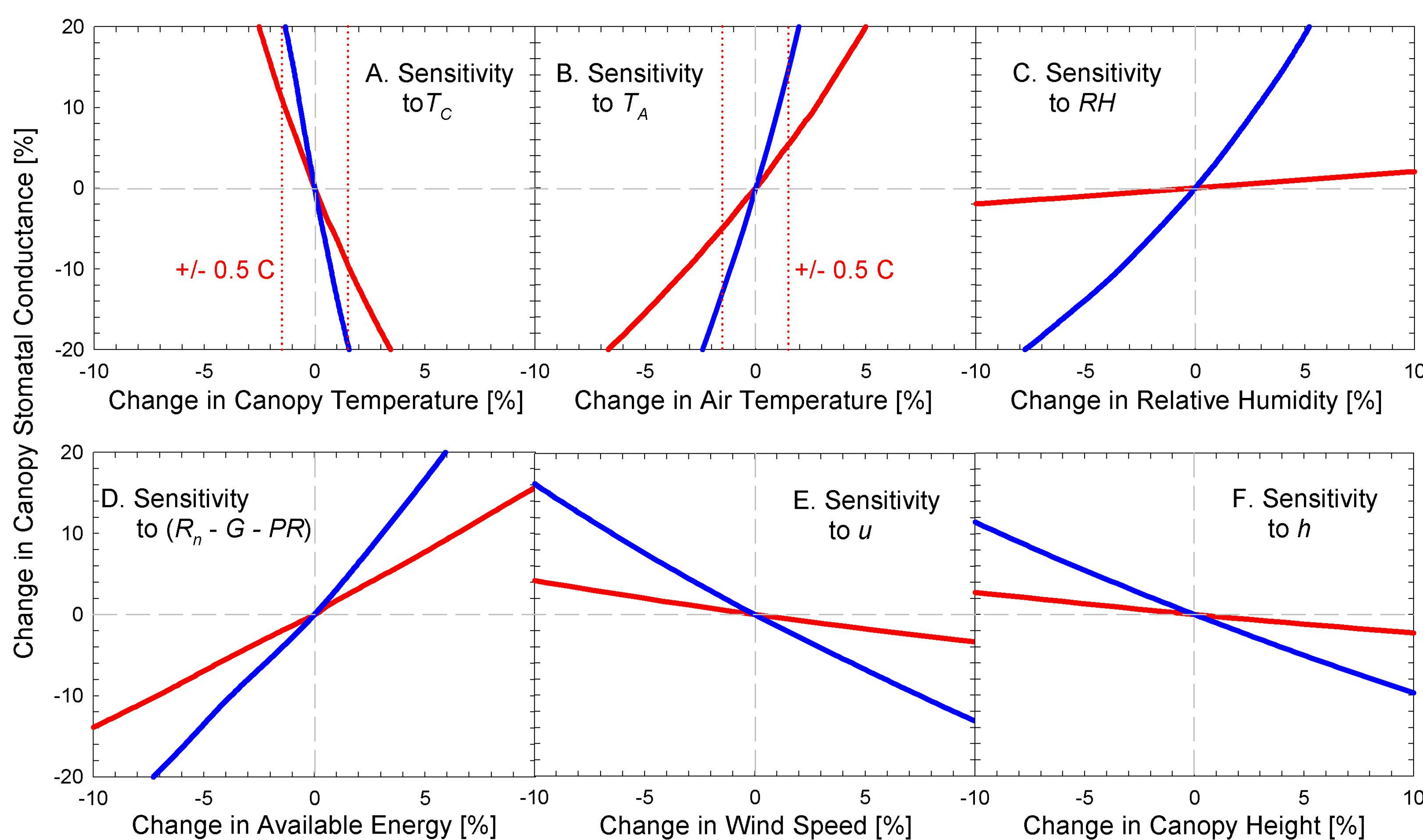
- 1 – Direct relationship to water flux from the plant canopy.
- 2 – Facilitates scaling from single leaf measurements to canopies.
- 3 – Normally distributed (∞ resistance = 0 conductance).



Relationship between stomatal resistance and stomatal conductance at constant air temperature and three barometric pressures.

Model Response and Sensitivity

Sensitivity analysis of g_C shows it is most sensitive to canopy temperature (T_C), followed by air temperature (T_A), with comparable sensitivity to the remaining measured parameters. The sensitivity of g_C to all measured parameters increases as conditions go from sunny, warm, and dry, to cloudy, cool, and humid.



Percentage change in g_C calculated with Eq. (1) in response to percentage changes in:

- Canopy Temperature (T_C).
- Air Temperature (T_A).
- Relative Humidity (RH).
- Available Energy ($R_n - G - PR$).
- Wind Speed (u).
- Canopy Height (h).

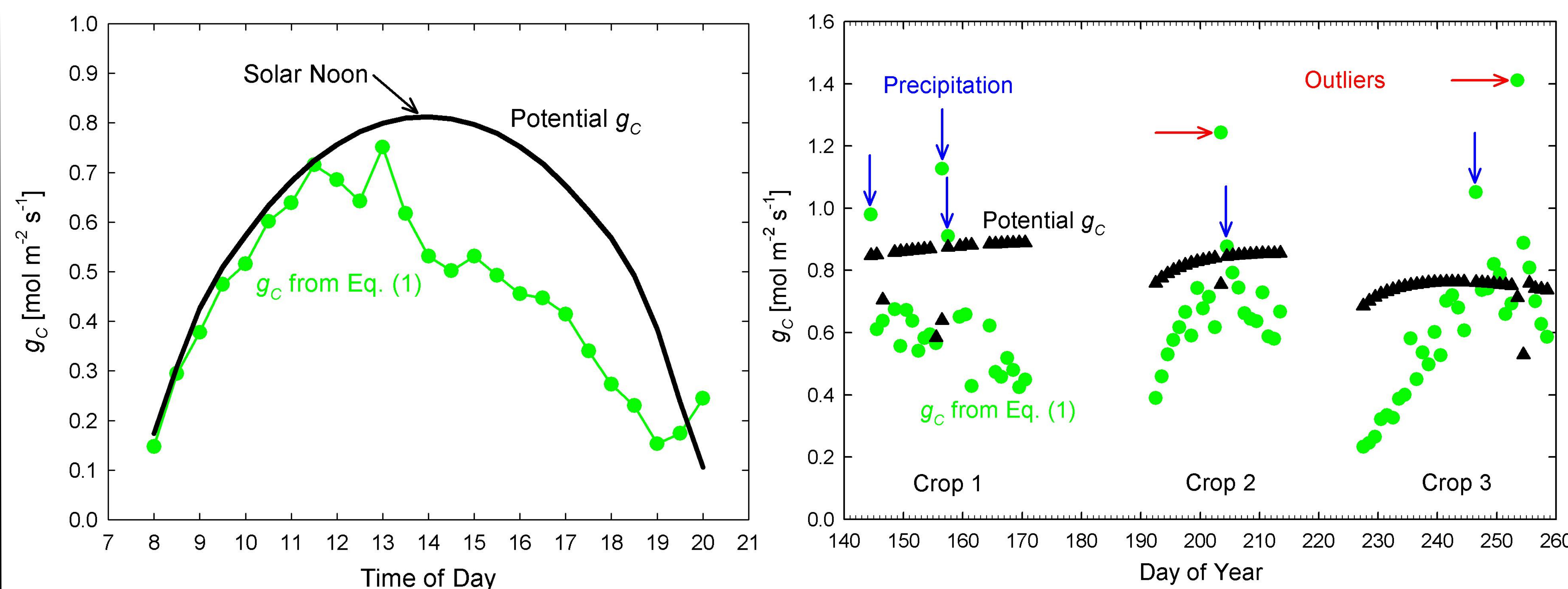
Sunny, Warm, Dry	Cloudy, Cool, Humid
$T_C = 33.7 \text{ C}$	$T_C = 12.6 \text{ C}$
$T_A = 35.0 \text{ C}$	$T_A = 10.0 \text{ C}$
$RH = 10.0 \%$	$RH = 80.0 \%$
$R_n = 650 \text{ W m}^{-2}$	$R_n = 150 \text{ W m}^{-2}$
$G = 65 \text{ W m}^{-2}$	$G = 15 \text{ W m}^{-2}$
$u = 2.0 \text{ m s}^{-1}$	$u = 2.0 \text{ m s}^{-1}$
$h = 0.5 \text{ m}$	$h = 0.5 \text{ m}$

Potential Canopy Conductance

A simple model was used to estimate maximum values of g_C , or potential g_C . The model assumes sunlit leaves in the canopy are the major contributors to g_C , and uses a calculated value of sunlit leaf area index to scale single leaf stomatal conductance to g_C . Single leaf conductance comes from the light response curve (stomatal conductance as a function of photosynthetically active radiation) for a well watered leaf. Potential g_C increases with plant growth (more leaf layers) and decreases on cloudy days (less radiation).

Measurements

Calculations of g_C from measurements for alfalfa in Logan, Utah, were compared to potential g_C values for summer 2008.



Canopy stomatal conductance (g_C) compared to potential g_C on July 14, a typical summer day where the alfalfa was well watered. In the morning g_C closely matches potential g_C , but deviates in the afternoon due to vapor pressure deficit effects. The model for potential g_C does not account for vapor pressure deficit.

Canopy stomatal conductance (g_C) compared to potential g_C at solar noon for three alfalfa crops. Major precipitation events are also marked to show g_C responds to water application. Two outliers are also marked, where g_C is well above potential g_C without a precipitation event.

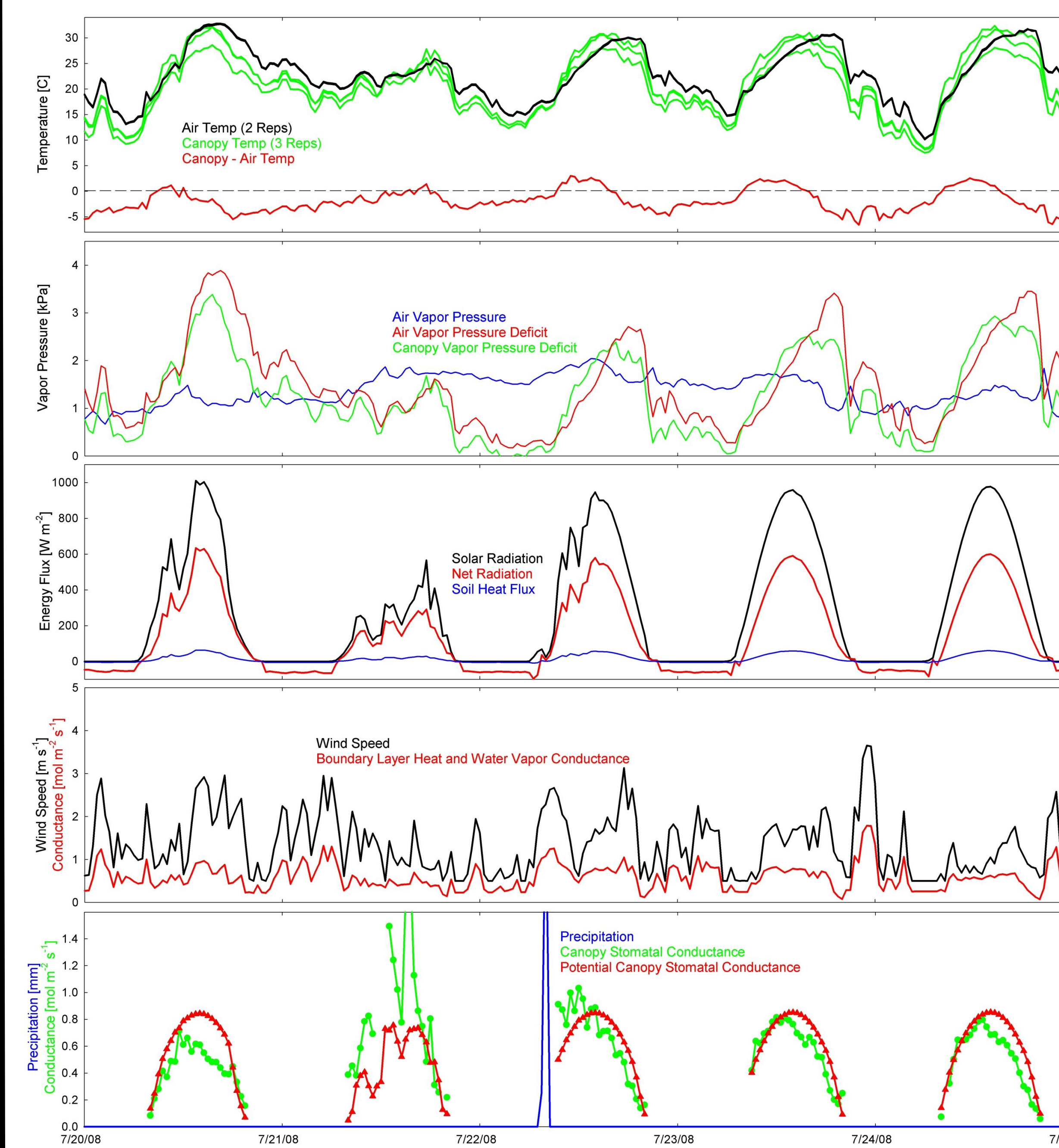


Photo of canopy stomatal conductance (g_C) weather station in Logan, Utah, and five days (July 25-20) of data from the station. Calculation of g_C matches potential g_C in the morning on July 20, then decreases in the afternoon. On July 21 g_C exceeds potential g_C for most of the day, likely due to measurement error under conditions of low vapor pressure deficit, net radiation, and wind speed. After the precipitation event on July 22, g_C exceeds potential g_C in the morning, then matches potential g_C the rest of the day and on July 23 and 24.

Summary and Conclusions

- 1 – We propose to abandon the use of relative and empirically-based plant stress indices in favor of canopy stomatal conductance (g_C), because g_C is a biophysical parameter that directly relates to stomatal plant water status and CO_2 uptake (plant growth and yield).
- 2 – Calculation of g_C can be used as a measure of plant water stress to indicate when to irrigate and can be used to supplement evapotranspiration and soil water content measurements. Measurements from alfalfa showed that g_C responded to precipitation events, with increases following rainfall.
- 3 – Comparison of g_C from measurements for alfalfa and potential g_C shows that g_C matches potential g_C except on cloudy, humid days with low wind speeds (difference likely due to measurement error) and immediately following irrigation events (difference likely due to soil conductance or potential g_C model).