
Assessment of Almond Water Status Using Inexpensive Thermographic Imagery

Project No.: HORT31.Bailey

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A. Summary

The overarching aim of this study is to develop a quick and inexpensive tool that can be used to evaluate almond tree water needs in order to help guide efficient irrigation practices. The original goal was to evaluate feasibility of inexpensive smartphone-based thermal cameras to measure leaf temperatures, which are used to infer leaf/canopy water status. Water lost by the leaf (transpiration) creates a cooling effect, and can reduce the leaf temperature to several degrees below the ambient air temperature in the case of a well-watered tree. As trees run out of water, transpiration begins to decline and the discrepancy between leaf and air temperature is reduced. However, transpiration is only one of several factors that affects the temperature of a leaf. A challenge is the separation of the effects of weather and environment from transpiration within the leaf temperature measurement, since ambient weather conditions also play an important role in determining the temperature of a leaf. This separation is typically performed using a crop water stress index or CWSI, which is purported to largely isolate the effects of plant water status within leaf/canopy temperature measurements.

We used a sensitivity analysis to show that the CWSI is as sensitive to wind speed as it is to plant water status, which can potentially introduce significant noise in the CWSI. This means that the CWSI must decline substantially before one can conclude that the tree has become “stressed”, because the decline in the CWSI itself must be much larger than the error in the CWSI measurement. We found this to be problematic in almond, potentially rendering the CWSI useless for irrigation scheduling in certain cases. Our experiments showed that during the period of low to moderate stress, the CWSI was relatively insensitive to changes in water status. Trees needed to be very stressed (e.g., 2 weeks without water) in order to observe a statistically significant decline in CWSI. We tried calculating the CWSI based on individual leaf temperature in the sun/shade, whole-canopy temperature, and only the upper sunlit portion of the canopy, and found a similar result in all cases. Physiological measurements also revealed that photosynthesis began to decline well before stomatal conductance, which indicated that even a

100% accurate temperature-based method may not be useful for irrigation scheduling. Initial results indicated that formulation of a modified CWSI based on the temperature of the trunk surface could potentially yield a water status indicator that was sensitive almost immediately following an irrigation event. Additional work is required to better evaluate the robustness of this approach.

B. Objectives

1. Goal(s) and specific objectives of the proposal

The main aim of this study was to develop and evaluate a methodology based on low-cost thermography that can be used to quickly evaluate tree water status and help guide irrigation decisions.

The research questions are:

Question 1. How does variation in environmental conditions (PAR, air temperature, relative humidity and wind speed) influence the crop water stress indices (CWSIs)?

Question 2. Can inexpensive thermography track the evolution of the water status decline of almond trees at various organ scales (leaf, canopy, or trunk) during a dry-down period?

Question 3. Can inexpensive thermography be used as a tool to schedule irrigation?

2. Annual outputs or milestones for each of the objectives

Table 1. Main Goal(s), key objectives, timelines and milestones

Main Goal: Evaluate whether low-cost infrared thermography can be used as a tool for almond irrigation scheduling		
Objective(s)	Date accomplished	Milestones and deliverables associated to the objective
Obj. 1 Develop a model for evapotranspiration (or other plant variables in connection with tree water status) inversion from thermographic imagery	July 2019	This objective is complete, and resulted in the submission of two scientific publications.
Obj. 2a Collect field data for methodological development and testing	September 2020	This objective produced experimental data for development and testing. We have completed three field seasons of data collection.
Obj. 2b Analyze field data for calibration and validation	December 2020	Analysis of data from years 1 and 2 has been used to quantify the performance of the method. A scientific publication was submitted in 2020. Additional analysis will continue following the 2020 field season.
Obj. 3. Develop a smartphone application (“app”) for distribution	N/A	Results to date suggest that thermography is not useful for irrigation scheduling in almond, and thus it will not be useful to develop an app. We instead continued work related to the previous objectives.

C. Results and Discussion

Obj. 1 - Impact of the environmental conditions and stomatal conductance on crop water stress indices (CWSI)

The goal of this component of the project was to better understand the impact of environmental conditions (PAR, air temperature, relative humidity and wind speed) and stomatal conductance on the CWSI. Ideally, we would like the CWSI to have low sensitivity to environmental factors, and high sensitivity to plant water status as indicated by variation in stomatal conductance. In order to quantify this sensitivity, a Morris sensitivity analysis was used to evaluate the impact of each parameter (environmental factors and stomatal conductance) on the CWSI value. We used the energy balance model to simulate the leaf temperature, the wet and dry reference surface temperature (components of CWSI) to evaluate four different formulations of CWSIs.

The most commonly used CWSI, defined here as $CWSI_2 = (T_{dry} - T_L) / (T_{dry} - T_{wet})$, showed the best ratio between the sensitivity of environmental factors and stomatal conductance. According to the results of the sensitivity analysis, $CWSI_2$ has the desirable trait that all environmental variables (except wind speed) appear to have a linear impact.

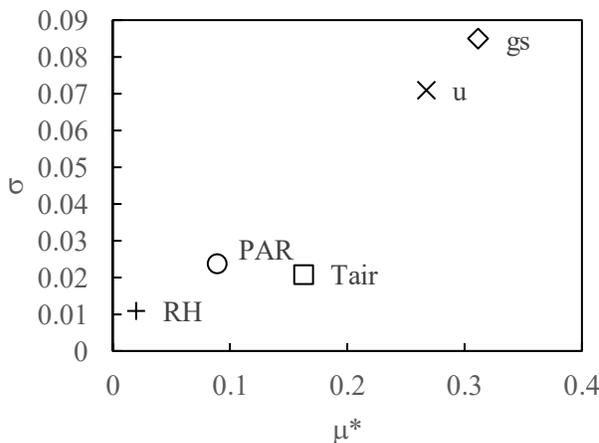


Figure 1 Example of global sensitivity analysis of CWSI (formulation 2) using the Morris method. Mean (μ^* ranks the parameters according to the magnitude of their impacts on the CWSI) and standard deviation (σ indicates the non-linear and/or parameter interaction effects) of the elementary effects of air temperature (T_{air}), relative humidity (RH), photosynthetically active radiation (PAR), wind speed (u), and stomatal conductance (g_s) on $CWSI_2$ in the sun. [see Publication 1 for the details]

This CWSI is moderately sensitive to light and air temperature, and highly sensitive to wind speed and stomatal conductance (Figure 1). This means that significant variation in CWSI could be observed without any change in water status. This could create significant error, and may mean that plants must be very stressed before a statistically significant decline in CWSI is observed.

We also demonstrated that even worse results were achieved if CWSIs were measured in shaded conditions (leaf/canopy scales). The lack of strong radiative forcing increases the impact of other environmental variables such as T_{air} and decreases the impact of g_s .

The complete results are described in publication 1, attached at the end of this report.

Obj. 2 – Tracking the CWSI of well-irrigated and non-irrigated trees at various scales/organs (leaf, canopy, trunk)

Previous work has repeatedly shown that the CWSI approach is able to ‘detect’ differences between a well-watered crop and a water stressed crop. However, this does not tell us whether the method can be used to schedule irrigation. A useful method should be able to detect the onset of stress soon after an irrigation event, and well before stomata have started to close significantly in response to declining water potential.

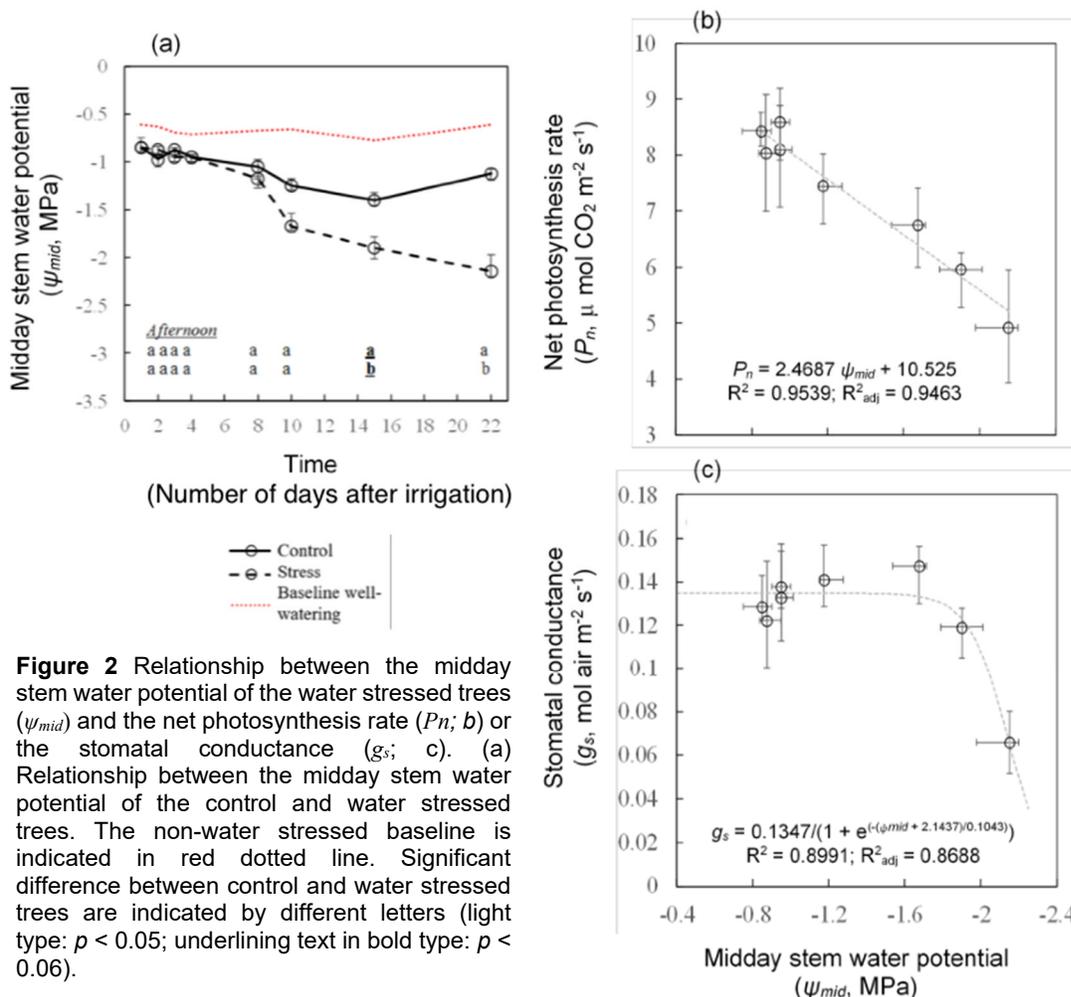
We conducted a dry-down experiment in which the decline in tree water status was closely followed through time following a heavy irrigation event that ensured the soil profile was full. The experiment was conducted in Davis, CA, using four-year-old nonpareil trees grafted on Krymsk 86 rootstock. A number of instruments, including the thermographic camera, were used to measure the plant response to the dry-down and ultimately the onset of stress, which was defined as the point at which stomata first began to close when subjected to constant leaf environmental conditions.

The dry-down was observed for two treatments, one in which no water was applied, and the other being ‘well-watered’. The midday water potential of the well-watered trees fluctuated around -0.9 MPa, which was slightly below the theoretical non-water stressed baseline (Figure 2a, red curve). The water status of the stressed trees gradually decreased from ca. -0.8 MPa to ca. -2.2 MPa during the non-irrigation period and was high (ca. -2.2 MPa) at the end of the measurement period (Figure 2a).

The stomatal conductance decreased after the midday water potential fell below approximately $\psi_{mid} = -1.7$ MPa (Figure 2c), indicating the onset of stomatal closure. Decline in photosynthesis rate occurred sooner at ψ_{mid} values below ca. -1.2 MPa (Figure 2b). When the stomata began to close, the net photosynthesis rate had fallen to about 20% of its maximum rate.

While measurements of stem water potential and stomatal conductance indicated a clear onset of water stress midway through the experiment, the CWSI based on thermal imagery showed very little variation at both the leaf and canopy scales (Figure 3). CWSIs measured at the leaf scale had high variability, and only toward the end of the experiment was there a statistically significant difference between the well-watered and drought stressed treatments. CWSIs calculated based on whole-canopy or upper-canopy measurements were much more consistent with lower variability. However, there was still little difference between the well-watered and water stressed treatments until the end of the experiment.

Based on the data we have collected, the CWSI based on leaf, whole canopy, and upper canopy temperature, we could not distinguish a significant difference between the ‘stress’ and ‘well-watered’ treatments until stress was substantial (long after stomata had started to close; Figure 3a, b, c). This means that by the time the method can reliably detect the onset of stress, it is probably too late and yield may be affected.



The basis of this project inherently assumes that photosynthesis and hence productivity and yield are primarily limited by stomatal closure as drought stress ensues. This assumption also underpins a number of water stress-sensing approaches, including porometry and nearly any method based on ET measurement. The basic idea is that as drought stress ensues, stomata begin to close which limits the rate of CO₂ diffusion into the leaf, which in turn leads to a reduction in carbohydrate levels that can translate into reduced growth and yield at some later time.

Our results suggested that this assumption may not be valid for almond trees, at least under the conditions present in this study. We found that stomatal conductance remained virtually constant for about 10 days after the last irrigation event was applied, whereas photosynthesis began to decline within a few days after irrigation. By the time that stomata began to respond to the reduction in water availability, photosynthesis had already declined to about 70% of its well-watered maximal value. Furthermore, the rate of decline in photosynthesis with time before and after initial stomatal closure appeared not to change. This suggested that even after stomata began to close, limitation of photosynthesis due to drought effects was primarily due to non-stomatal effects.

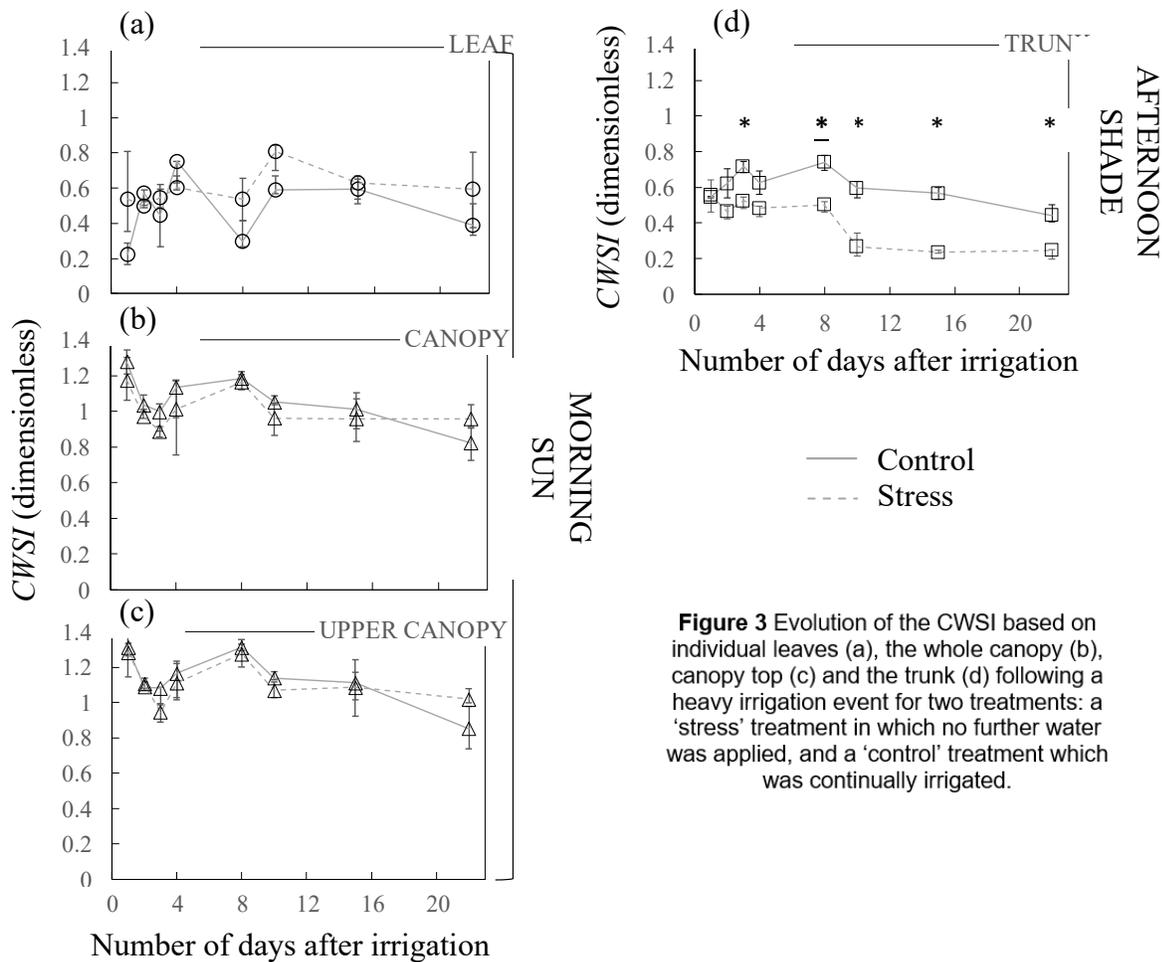


Figure 3 Evolution of the CWSI based on individual leaves (a), the whole canopy (b), canopy top (c) and the trunk (d) following a heavy irrigation event for two treatments: a 'stress' treatment in which no further water was applied, and a 'control' treatment which was continually irrigated.

We did find evidence suggesting a CWSI based on trunk temperature could be a sensitive indicator of plant water status starting soon after the dry-down began (Figure 3d). There was a significant difference between the trunk CWSI for the control and stressed treatments, that tracked closely with the decline in photosynthesis. If this difference is indeed physical, this would tend to indicate that the decline in the trunk CWSI due to drought stress is primarily due to the decline in water potential (and perhaps associated impacts on hydraulic conductivity) rather than stomatal effects on ET. These results need to be further verified with additional experiments.

It should be emphasized that the above results are limited to a single orchard, cultivar, and rootstock, and thus more work is needed to evaluate the robustness of results. The soil texture present at the experimental site had good water-holding capacity, which likely helped to create the conditions needed for prolonged stomatal opening. If soil conditions are poor, it is possible that full tree rehydration and stomatal opening will never be achieved, in which case the trees will always lie on the sloped portion of the curve plotted in Figure 2c.

If results are shown in the future to be robust across a wide range of cultivars and locations, this would imply that any water stress measurement method based on stomatal conductance, or more broadly ET measurement, could be largely decoupled from photosynthetic production and ultimately yield.

Conclusion

In many cases, thermography may be able to detect areas of the orchard with significant variation in plant water status at any single instant in time, provided that there is a substantial level of stress in these areas. However, we have not yet found evidence to suggest that thermography along with the traditional leaf/canopy CWSI is a potentially viable tool for scheduling irrigation because of the lack of sensitivity of the CWSI throughout time as water status declines following an irrigation event. Our results indicated that the traditional CWSI is moderately sensitive to light and air temperature, and highly sensitive to wind speed. This may contribute to lack of sensitivity of the CWSI during the initial period when stomata begin to close. Furthermore, results indicated that there is a much tighter correlation between stem water potential and photosynthesis than stomatal conductance and photosynthesis during the period of initial drought onset. This means that, even if the CWSI was a perfect indicator of stomatal closure in response to drought, it may not be useful for irrigation scheduling because limitation on photosynthesis due to drought appeared primarily due to non-stomatal effects.

Future work could further improve calculation of CWSIs by developing a normalization that can remove the impact of the wind speed. It is also necessary to verify results for other almond cultivars and soil textures. Finally, additional experiments are needed to explore the calculation of the CWSI based on trunk temperature (i.e., improve the formulation of the stress index).

D. Outreach Activities

1. Outreach activities including the event description
 - Almond Board Conference in 2017, 2018, and 2019.
 - Invited Talk: "Development of the Next Generation of Perennial Crop Modeling Tools", CalASA/California Plant and Soil Conference, Fresno, CA.

E. Materials and Methods (500 word max.):

1. Outline materials used and methods to conduct experiment(s)

Plant material

Experiments were conducted during the 2018-2020 growing seasons in the same experimental orchard located in the UC Davis pomological orchards immediately to the west of the main UC Davis campus (38°32'16" N, 121°47'42" W). We used the *Prunus dulcis* cultivar "Nonpareil" grafted on Krymsk 86 rootstock.



Figure 4 Experimental almond orchard used in the study (in collaboration with Dr. Astrid Volder, U.C. Davis).