A Comprehensive Stress Index for Evaluating Plant Water Status in Almond Trees

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Abstract. *This study evaluated a comprehensive plant water stress index that integrates the canopy temperature and the environmental conditions that can assist in irrigation management. This index—Comprehensive Stress Index (CSI)—is based on the reformulation of the leaf energy balance equation. Specifically, CSI is the ratio of the temperature difference between a dry leaf (i.e. a leaf with a broken stem) and a live leaf (on the same tree) [i.e. T_{dry}-T_{leaf}] and the difference between the vapor pressure inside the stomatal cavity at saturation and the vapor pressure of the air at ambient temperature [i.e. $e_s(T_L)$-$e(T_A)$]. The required measurements to compute CSI include dry leaf temperature, live leaf temperature, relative humidity, and air temperature at the tree being monitored. In this study, all measurements were obtained using a single sensor suite per tree connected to a wireless mesh network. The sensor suite included two thermal infrared sensors, one for the dry leaf and one for the live leaf, both of which were housed in the same unit with approximately the same environmental conditions. The CSI is a dynamic index with a value for every data sample collected. For a single index representing each day, the CSI was manipulated in two ways. First, the CSI was integrated with respect to time from 10 AM to 6 PM to obtain the Integrated Comprehensive Stress Index (ICSI). Second, the CSI was averaged from 1 PM to 3 PM to obtain the Average Comprehensive Stress Index (ACSI). Both ICSI and ACSI were compared to other stress indices, including CWSI and IDANS. Results indicate that ICSI and ACSI are satisfactorily correlated with midday stem water potential (SWP). The ICSI and ACSI indices may be more convenient than other stress indices because they require measurements only at the tree being monitored.*

Keywords. *infrared thermometry, deficit irrigation, stem water potential, crop water stress index, integrated degrees above non-stressed.*

1.0 Introduction

Limited water resources and increasing food demands from a growing world population has led researchers to seek improved precision irrigation practices. Irrigation in California used an average of 60.7% of total water withdrawals, or approximately 23 billion gallons of water, per day in 2010 (USGS, 2017). California is the top producer in the world of one of the most water-thirsty specialty crops: almonds (ABC 2015). Almonds were California's third most valuable agricultural commodity, worth $5.16 billion in 2016 (CDFA, 2016). The combination of high value and large water requirement has motivated researchers to develop improved techniques for sustainable irrigation management of almond orchards.

Thermal infrared sensing to measure leaf temperature is one of the most convenient, inexpensive, and accurate options available on the market for quantifying the physiological water status of the plant to aid in irrigation scheduling (Jones, 2003). When the plant is not under stress, the stomata open and transpiration occurs, leading to cooling of the leaf due to transpiration. When the plant is under stress, the stomata close and no cooling due to transpiration occurs, so the leaf temperature is approximately the same as the ambient air temperature (Hsiao, 1973).

The canopy or leaf temperature can be converted into a stress index that can be used for irrigation management. Several stress indices utilizing canopy temperature have been developed. A conventional method for assessing plant water status (PWS) is by computing the Crop Water Stress Index (CWSI) (Idso, Jackson, Pinter, Reginato, & Hatfield, 1981; Jackson, Idso, Reginato, & Pinter, 1981). The empirical form of CWSI (Idso et al., 1981) requires the difference between the air temperature and the canopy temperature as well as the lower baseline (saturated leaf condition) and the upper baseline (dry leaf condition) air-canopy temperature differentials:

$$CWSI = \frac{(T_{air} - T_m) - (T_{air} - T_{sat})}{(T_{air} - T_{dry}) - (T_{air} - T_{sat})}$$

where T_{air} is the ambient air temperature, T_m is the measured canopy or leaf temperature of the canopy or leaf being monitored for stress, T_{sat} is the temperature of a saturated or non-water stressed canopy, and T_{dry} is the temperature of a non-transpiring or dry canopy.

Another canopy temperature-based index is Degrees Above Non-Stressed (DANS) (Taghvaeian, Comas, DeJonge, & Trout, 2014). The DANS index is simpler than the empirical form of CWSI because it only requires temperatures of stressed and non-stressed canopies and not air temperature. DANS is the difference between the temperature of a stressed canopy (T_S) and the temperature of a non-stressed canopy (T_{NS}):

$$DANS = T_S - T_{NS}$$

The DANS is a dynamic index with a value for each data sample collected, which may be several times per day. DANS can be integrated over the day to evaluate a daily stress index called Integrated Degrees Above Non-Stressed (IDANS) (DeJonge, Taghvaeian, Trout, & Comas, 2015):

$$IDANS = \int_{t_1=0\ hr}^{t_2=24\ hr} (T_S - T_{NS})\, dt$$

Although these daily stress indices, IDANS and CWSI, provide useful insight into the physiological water status of the plant, they require the leaf temperature of multiple leaves—the saturated leaf and the leaf being monitored for stress—to describe the water status of the leaf of interest. All leaves have slightly different characteristics such as the frequency of stomata the number of stomata per unit area, which affects the plant's ability to transpire through that leaf (Willmer &

Fricker, 1996). Stress indices that require the temperature of different leaves (e.g. the stressed leaf, the non-stressed leaf) do not account for the differences in the number of stomata per unit area of the leaves. Furthermore, farmers may not want to invest in additional piping to provide a section of their orchard with extra water to simulate the lower baseline.

The goals of this study were to:

- Develop a comprehensive stress index that integrates the leaf temperature and the environmental conditions (e.g. relative humidity and air temperature) and avoids the use of the canopy temperature-air temperature differential from the non-stressed baseline eliminating the uncertainty introduced by using leaves with varying numbers of stomata per unit area.
- Compare the stress index from (1) to midday stem water potential and other stress indices, including CWSI, DANS, and IDANS.

2.0 Materials and Methods

2.1 Deriving the Comprehensive Stress Index

In this study, a comprehensive stress index was derived from the energy balance of a leaf. The resulting stress index, CSI, compares the difference between the temperature of a monitored leaf and a dry leaf and the difference between the vapor pressure in the stomatal cavity at saturation of the monitored leaf and the water vapor pressure in the surrounding air at ambient temperature. The derivation of CSI will be described in the next sections, beginning with the energy balance on a leaf. Table 1 defines the variables in the derivation of CSI.

Table 1. Description of Variables for Deriving the Comprehensive Stress Index

Variable Symbol	Description	Units
ρ	Density of the air	kg/m^3
c_p	Specific heat capacity of air	1012 J·kg^{-1}·K^{-1}
A	Area of the leaf	m^2
z	Thickness of the leaf	m
T_L	Leaf temperature	K
T_A	Air temperature	K
T_D	Dry leaf temperature	K
h	Convective heat transfer coefficient	W·m^{-2}·K^{-1}
R_n	Net heat gain from radiation	W·m^{-2}
L	Latent heat of vaporization	J·kg^{-1}
N	Number of stomata on the leaf	
n	Number of stomata per unit area	
$e_s(T_L)$	Saturation vapor pressure in the stomatal cavity at leaf temperature	kPa
$e_s(T_A)$	Saturation vapor pressure in the air at ambient temperature	kPa
$e(T_A)$	Water vapor pressure in the air at ambient temperature	kPa
r_s	Stomatal resistance	m·s·mmol^{-1}
r_a	Boundary layer resistance to water vapor	m·s·mmol^{-1}

The leaf energy balance is expressed in equation (1):

$$\rho c_p A z \frac{dT_L}{dt} = AR_n - hA(T_L - T_A) - LN\left(\frac{e_s(T_L) - e(T_A)}{r_a + r_s}\right) \quad (1)$$

Where the saturation vapor pressure in the stomatal cavity [i.e. $e_s(T_L)$] and in the air [i.e. $e_s(T_A)$] can be described by the Tetens formula in equations (2) and (3), respectively, and the non-saturation water vapor pressure in the air can be found by adjusting $e_s(T_A)$ by the local relative humidity, as shown in equation (4), where the temperatures are in ℃.

$$e_s(T_L) = 0.6108 * exp\left(\frac{17.27 * T_L}{T_L + 237.3}\right) \quad (2)$$

$$e_s(T_A) = 0.6108 * exp\left(\frac{17.27 * T_A}{T_A + 237.3}\right) \quad (3)$$

$$e(T_A) = e_s(T_A) * \frac{RH}{100} \quad (4)$$

In developing CSI, the leaf was assumed to be at steady state because the leaf temperature does not change very much during small periods of time. Data for this study were collected every fifteen minutes, during which minimal changes in the canopy temperature were observed. The changes in canopy temperature within the fifteen minutes between measurements were typically less than the accuracy of the infrared thermal sensor (±0.5 ℃). Since the leaf temperature differences were small in between measurements, the energy balance can be simplified to the following equation:

$$0 = AR_n - hA(T_L - T_A) - LN\left(\frac{e_s(T_L) - e(T_A)}{r_a + r_s}\right) \quad (5)$$

The terms were rearranged to obtain an equation for the temperature difference between the leaf and the air:

$$(\boldsymbol{T_L} - \boldsymbol{T_A}) = \frac{\boldsymbol{R_n}}{\boldsymbol{h}} - \frac{\boldsymbol{LN}}{\boldsymbol{hAr_a}}\left(\frac{\boldsymbol{e_s(T_L)} - \boldsymbol{e(T_A)}}{1 + {}^{r_s}/_{r_a}}\right)$$

(6)

In the following two equations, some of the terms were re-defined to simplify the equation. The convective heat transfer coefficient is inversely related to the boundary layer resistance, leading to the following relationship:

$$\frac{1}{r_a} \propto \boldsymbol{h} \rightarrow \frac{1}{r_a} = \boldsymbol{\alpha h} \quad (7)$$

In addition, the number of stomata can be converted into a density of stomata (i.e. number of stomata per unit area):

$$\boldsymbol{n} = \frac{\boldsymbol{N}}{\boldsymbol{A}} \quad (8)$$

The following equation reflects the redefined terms from equations (7) and (8):

$$(\boldsymbol{T_L} - \boldsymbol{T_A}) = \frac{\boldsymbol{R_n}}{\boldsymbol{h}} - \frac{\boldsymbol{Ln}}{\boldsymbol{\alpha}}\left(\frac{\boldsymbol{e_s(T_L)} - \boldsymbol{e(T_A)}}{1 + {}^{r_s}/_{r_a}}\right) \quad (9)$$

Two physiological conditions should be considered in this energy balance equation: (1) the lower baseline or saturated leaf condition and (2) the upper baseline or dry leaf condition. For the case of the saturated leaf condition, the following assumption was made:

$$\frac{r_s}{r_a} \rightarrow 0$$

When the leaf is saturated, equation (9) becomes:

$$(\boldsymbol{T_L} - \boldsymbol{T_A}) = \frac{\boldsymbol{R_n}}{\boldsymbol{h}} - \frac{\boldsymbol{Ln}}{\boldsymbol{\alpha}}\left(\boldsymbol{e_s(T_L)} - \boldsymbol{e(T_A)}\right)$$

(10)

For the case of the dry leaf condition, the following two assumptions were made:

$$\frac{\mathrm{r_s}}{\mathrm{r_a}} \rightarrow \infty$$

$$\mathrm{T_L} = \mathrm{T_D}$$

Since the leaf is dead, the cooling effect due to transpiration would be zero, resulting in the following reduced version of equation (9):

$$(\mathrm{T_D} - \mathrm{T_A}) = \frac{\mathrm{R_n}}{\mathrm{h}} \quad (11)$$

The temperature difference between the dry leaf and the air is directly related to the net heat gain due to radiation and inversely related to the convective heat transfer coefficient. The net heat gain due to radiation and the convective heat transfer coefficients are approximately the same for both a dry leaf and a live leaf because they are co-located within the leaf monitor. Therefore, the left-side of equation (11), (T_D-T_A), can be substituted for the $\frac{R_n}{h}$ term in equation (9). This transforms equation (9) to the following equation:

$$(\mathbf{T_L} - \mathbf{T_A}) = (\mathbf{T_D} - \mathbf{T_A}) - \frac{\mathbf{Ln}}{\boldsymbol{\alpha}}\left(\frac{\mathbf{e_s(T_L) - e(T_A)}}{\mathbf{1 + {}^{r_s}/_{r_a}}}\right) \tag{12}$$

Equation (12) can be simplified to:

$$(\mathbf{T_L} - \mathbf{T_D}) = -\boldsymbol{\beta}\left(\frac{\mathbf{e_s(T_L) - e(T_A)}}{\mathbf{1 + {}^{r_s}/_{r_a}}}\right) \tag{13}$$

$\beta = \frac{Ln}{\alpha}$ is a constant

Rearranging equation (13) leads to the Comprehensive Stress Index (CSI):

$$\mathbf{CSI} = \frac{\mathbf{(T_D - T_L)}}{\mathbf{e_s(T_L) - e(T_A)}} = \frac{\boldsymbol{\beta}}{\mathbf{1 + {}^{r_s}/_{r_a}}} \tag{14}$$

According to equation (14), the CSI is related to the stomatal resistance (e.g. the inverse of the stomatal conductance). The CSI is also a function of the number of stomata per unit area on the leaf.

In this study, the CSI was computed every fifteen minutes, resulting in a dynamic stress index. To obtain a daily stress index, the CSI was modified in two ways. The first daily stress index is the Integrated Comprehensive Stress Index and was defined as:

$$\mathrm{ICSI} = \int_{t_1 = 10\ \mathrm{AM}}^{t_2 = 6\ \mathrm{PM}} \frac{(T_D - T_L)}{e_s(T_L) - e(T_A)}\, dt \tag{15}$$

The period from 10 AM to 6 PM was selected because that is the period when the canopy is doing most of its photosynthesis during the day. Before 10 AM, condensation on the leaf can cause the canopy temperature to be above the air temperature. This would result in a negative T_A-T_L, which can be confusing to interpret, especially when integrating over time.

The second daily stress index is the Average Comprehensive Stress Index and was defined as:

$$\mathrm{ACSI} = \frac{1}{t_2 - t_1} \int_{t_1 = 1\ \mathrm{PM}}^{t_2 = 3\ \mathrm{PM}} \frac{(T_D - T_L)}{e_s(T_L) - e(T_A)}\, dt \tag{16}$$

The period from 1 PM to 3 PM was selected because that is around solar noon when midday stem water potential measurements are typically done.

2.2 Plant and Environmental Measurements

The data for this study was collected with an existing sensor suite (Dhillon, 2015), called the 'leaf monitor,' that continuously and proximally measures air temperature, leaf temperature, relative humidity, wind speed, and photosynthetically active radiation. The sensor suite includes an inexpensive thermal infrared sensor (MLX90614, Melexis Technologies, NV) to measure the leaf temperature. Several units of this sensor suite were connected to a wireless mesh network to provide continuous real-time data.

The development of CSI was part of a larger regulated deficit irrigation (RDI) study, in which sixteen non-pareil almond trees were each monitored with a leaf monitor during the 2017 growing season at Nickels Soil Lab in Arbuckle, CA, USA (Kizer, 2018). One tree received extra water to simulate the saturated condition. A leaf monitor was installed on this well-watered tree to obtain a lower baseline to compute CWSI. In addition, midday stem water potential (SWP) measurements were taken at each tree with a leaf monitor two or three times a week during the 2017 growing season.

This study used a four-acre plot consisting of five rows of non-pareil almond trees bordered on either side by pollinator trees. The plot was separated into two management zones delineated by soil and plant characteristics (Kizer et al., 2017). Within each management zone, there were both grower and regulated deficit irrigation treatments. The RDI treatments were irrigated at percentages of the total crop evapotranspiration since the last irrigation. The percentage of ET was determined by looking at relative increases and decreases in CSI from day to day. Different amounts of irrigation were applied to each management zone in the RDI treatments based on the CSI.

3.0 Results and Discussion

3.1 Dynamic Comprehensive Stress Index

A dynamic CSI was computed on a quarter-hourly basis for each tree. Time series plots of CSI like that shown in Fig. 1 were produced for each monitored tree daily during the growing season in 2017. These plots served as the primary tool for evaluating changes in plant water stress from day to day. Based on equation 14, the value of the dynamic CSI should increase when the stomatal conductance increases (i.e. when the stomatal resistance decreases), so there is less resistance to transpiration. During the 2017 growing season, the plant water stress was evaluated daily by observing increases or decreases in the dynamic CSI in relation to when irrigation events happened. Since the CSI is a function of the number of stomata per unit area on the leaf, it was difficult to establish an amount of increase or decrease in CSI to use as a threshold for triggering an irrigation event that works for any almond tree. The CSI was evaluated separately for each monitored tree because of the dependence of CSI on the number of stomata per unit area on the leaf. When the time series plot showed consecutive decreases in CSI over several days, this indicated that the stomata were closing to prevent further water loss. At that point, irrigation was applied in the RDI treatments to avoid further stress. For the grower treatment, the changes in CSI from day to day were observed but not used for irrigation management.

The example CSI time series plots in Fig. 1 show high CSI values on July 22 followed by decreasing CSI values on July 23 to reach relatively steady low CSI values on July 24-25. The declining CSI values indicate a period of increasing stress levels due to depleting water availability. The CSI did not immediately respond to the irrigation applied on July 26, but did increase the next day on July 27 and even more on July 28.

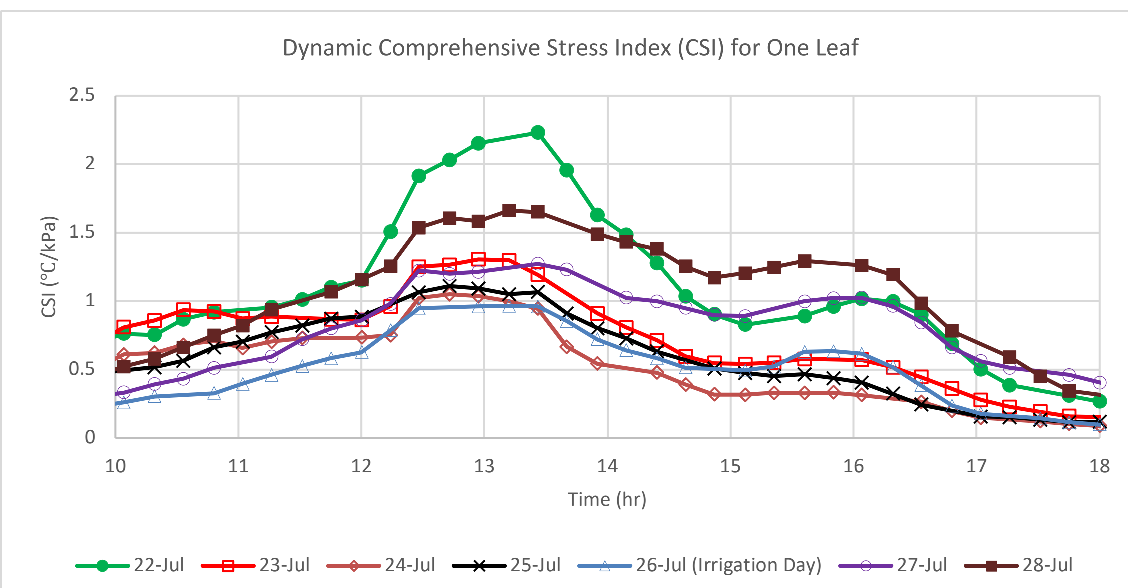

Figure 1: An example of the Comprehensive Stress Index time series plot for one leaf from July 22 to July 28, 2017.

The CSI time series plots were compared to Degrees Above Non-Stressed (DANS) time series plots. As DANS increases, the temperature difference between the saturated leaf and the monitored leaf increases. When DANS approaches zero, the monitored leaf temperature is closer to the saturated leaf temperature, indicating that the monitored canopy is fully transpiring. An example of the DANS time series plot demonstrates the behavior of the monitored canopy in relation to the saturated canopy (Fig. 2). From July 22 to July 23 the temperature of the monitored canopy departs from the temperature of the saturated canopy until reaching a relatively steady DANS on July 24 and July 25. When the monitored canopy was irrigated on July 26, the temperature already started approaching the temperature of the saturated canopy again. On July 27 and July 28, the DANS reached a relatively steady low, indicating that the monitored canopy was transpiring but still not as much as the saturated canopy.

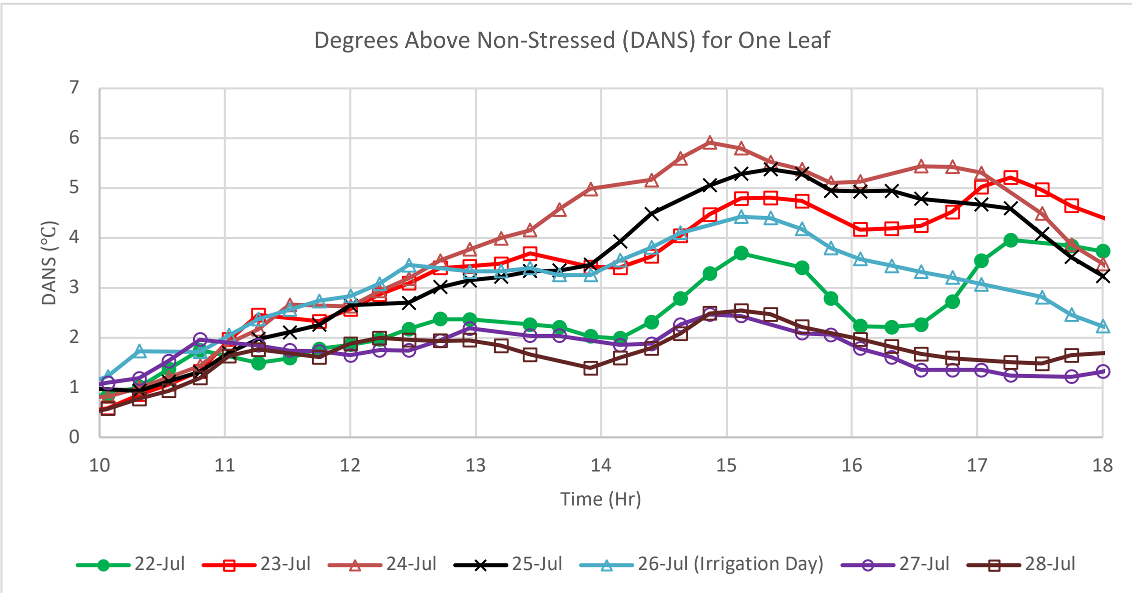

Figure 2: Degrees Above Non-Stressed for one leaf from July 22 to July 28, 2017.

The CSI and DANS time series plots indicate similar physiological responses of the monitored canopy in response to irrigation events. Like DANS, the CSI time series plots can serve as a tool for implementing regulated deficit irrigation. The CSI can be monitored over several days of increasing stress before applying an irrigation rather than irrigating at regular intervals that may not reflect the physiological tolerances of the plant to soil water deficit. Although the dynamic CSI is useful, a single daily stress index would be more comparable to midday stem water potential as well as other stress indices, such as CWSI and IDANS.

3.2 Correlation of daily stress indices with stem water potential

The stem water potential was compared with ICSI, ACSI, IDANS, and CWSI for individual leaves. A sample of three leaves that were monitored are included in the following results. For each subplot in Fig. 3, the same leaf was used for all observations of the stress indices to avoid uncertainty associated with different numbers of stomata per unit area of different leaves. Stem water potential was measured on a leaf from the same tree as the monitored leaf. For most trees there was a good agreement between ACSI, ICSI and SWP.

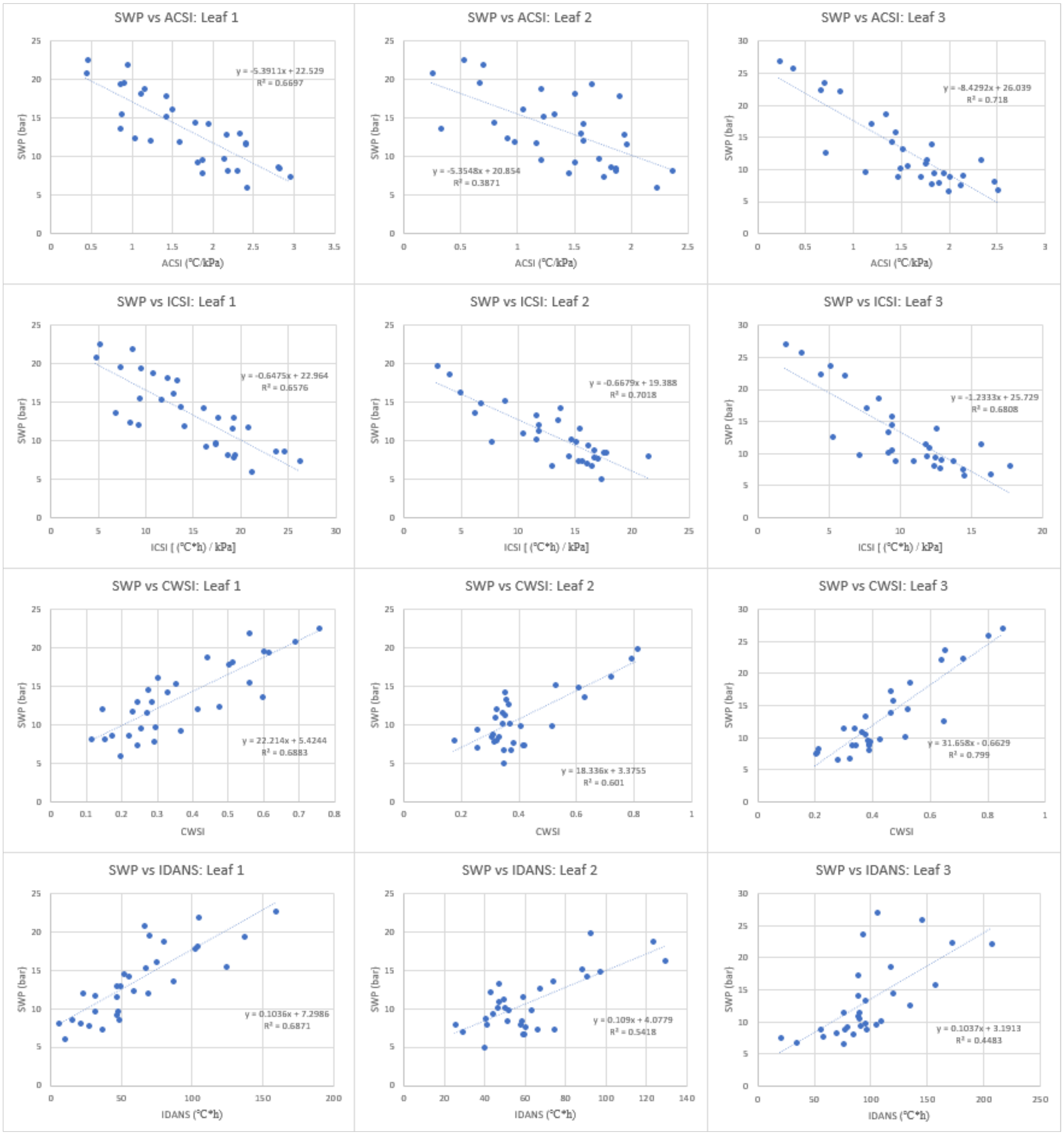

Figure 3: Top Row: Midday Stem Water Potential versus Average Comprehensive Stress Index for three different leaves. Second Row from Top: Midday Stem Water Potential versus Integrated Comprehensive Stress Index. Third Row from Top: Midday Stem Water Potential versus Crop Water Stress Index. Bottom Row: Midday Stem Water Potential versus Integrated Degrees Above Non-Stressed.

4.0 Conclusions

A one-year study evaluated the use of the dynamic Comprehensive Stress Index (CSI) for quantifying the plant water status in almond trees. Irrigation was applied when the CSI indicated a consistent increase in the water stress level. Further analysis of the data after the growing season led to the development of two new daily stress indices: Integrated Comprehensive Stress Index (ICSI) and Average Comprehensive Stress Index (ACSI). These new stress indices were compared to existing daily stress indices, CWSI and IDANS, and were found to be correlated with each other. The ICSI and ACSI indices were also found to be correlated with midday stem water potential at similar levels to CWSI and IDANS. Low correlations with midday stem water potential were found in the same leaves for all stress indices and vice versa. Further research should investigate the cause of low correlations between these stress indices and SWP for certain leaves and not others. The leaf selected to measure leaf temperature may not have been representative of the tree, thus not strongly correlated with midday stem water potential. While this is only a conjecture, further research needs to validate whether poor leaf selection for the leaf temperature measurement impacted the correlation with SWP. Additionally, the number of stomata per unit area may influence the magnitude of CSI, ACSI, and ICSI, so further research should focus on converting these stress indices into a normalized stress index (e.g. ranging from 0 to 1 like CWSI) while avoiding measurements from a lower baseline (e.g. saturated leaf).

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