Continuous Monitoring of Wine Grape Canopy Temperature for Irrigation Management

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Abstract. *Automated monitoring of plant water status is a prerequisite for precision irrigation and water conservation. The objective of this study was to assess the potential for using a thermal-based crop water stress index (CWSI) as an irrigation management tool to assist with scheduling irrigation events and estimating irrigation amounts for selected wine grape cultivars in the arid Northwest U.S. The temperature of the vine canopy, soil volumetric water content, vineyard environmental conditions, irrigation events and amounts were continuously monitored in field plots of the wine grape cultivars Malbec and Chardonnay at three commercial vineyards in southwestern Idaho during the 2017 growing season. Select measured and calculated parameters were made available in real-time to vineyard managers on a website hosted by the data logger via cell phone modem. At all sites, the daily CWSI rapidly decreased during and following an irrigation event and gradually increased between irrigation events, indicating sensitive and rapid response to changes in available soil moisture. Throughout the growing season, the change in CWSI value reflected the relationship between plant available soil water (PASW) and the water stress coefficient (Ks) of the Penman-Monteith equation for estimating plant water demand. Data analysis suggests that automated calculation of a daily CWSI through continuous remote monitoring of vine canopy temperature and vineyard environmental conditions can be used to guide irrigation scheduling and estimate the reduction in vine water demand when transpiration is restricted by soil water availability.*

Keywords. Crop water stress index, wine grape, drip irrigation, automation.

Introduction

Wine grapes (*Vitis vinifera* L.) are widely grown in arid and semiarid regions where irrigation is used to supplement annual precipitation and maintain a desirable level of vine water stress. Decisions about when to irrigate and how much water to supply during an irrigation event ultimately influence production profitability in terms of input costs, yield and fruit quality. Determining when to irrigate and how much water to supply during an irrigation event can be challenging due to the lack of an easy, reliable method for readily assessing the severity of vine water stress.

Measurements of soil moisture and plant water potential have been used to monitor vine water stress, but each have limitations that restrict their usefulness in an automated system. Williams and Trout

(2005) found that measurement of soil water content to a depth of 3m at nine locations within one-quarter of an individual vine root zone was necessary to accurately determine the amount of water within the soil profile that was available to drip-irrigated grapevines. The low spatial resolution was due to heterogeneous soil attributes, such as texture and depth, spatially heterogeneous irrigation wetting patterns (drip irrigation) and spatially heterogeneous rooting characteristics. Thus, numerous soil moisture monitoring sites would be needed to reliably infer vine water stress status. There is no general agreement as to which measurement of plant water potential (pre-dawn leaf or midday stem or leaf) most reliably indicates vine water status (Williams and Araujo 2002, Williams and Trout 2005, Ortega-Farias et al. 2012). Williams and Trout (2005) found that pre-dawn leaf water potential was unsatisfactory for accurately determining vine water status while midday leaf and stem water potential were linearly correlated and equally suitable for determining vine water status. Midday leaf water potential is the most common method used in California to indicate vine water status (Williams et al. 2012) perhaps because it is less time consuming than either pre-dawn leaf water potential or midday stem water potential allowing more acreage to be covered during optimum midday climatic conditions (Williams and Araujo 2002). Measuring leaf or stem water potential is labor intensive and values can be strongly influenced by environmental conditions (Rodrigues et al. 2012, Williams and Baeza 2007, Jones 2004). Under semi-arid conditions, the influence of vapor pressure deficit (VPD) on midday stem or leaf water potential has been found to differ according to severity of water stress (Williams and Baeza 2007, Williams et al. 2012). Under high evaporative demand, a midday value of leaf water potential less negative than -1.0 MPa has generally been accepted as indicative of well-watered vines (Shellie 2006, Williams and Trout 2005, Williams et al. 2012, Shellie and Bowen 2014, Bellvert et al. 2015).

Thermal remote sensing has been used to estimate drought stress in many crops, including grapevine (Maes and Steppe, 2012). A temperature-based crop water stress index (CWSI), developed by Jackson et al. (1981) and Idso et al. (1981), was found to more reliably indicate plant water status than soil volumetric water content (Jackson, 1982). The empirical CWSI is calculated as:

$$CWSI = \frac{(T_{canopy} - T_{LL})}{(T_{UL} - T_{LL})} \tag{1}$$

where T_{canopy} is the measured temperature of the vine canopy, and T_{UL} and T_{LL} are the upper and lower canopy temperature thresholds when transpiration is completely limited and non-restricted, respectively. The CWSI ranges in value from 0 to 1 where 0 indicates optimum conditions for maximum transpiration (T_{LL}) and 1 represents a non-transpiring condition (T_{UL}). The need to schedule an irrigation event is signaled when the CWSI value exceeds a desired numerical threshold established by field experiments.

The amount of water to supply during an irrigation event to meet estimated plant water demand is commonly estimated using the Penman-Monteith equation (Allen et al., 1998). The equation used to estimate actual daily evapotranspiration ($ET_{c\ act}$) when environmental conditions, such as drought, limit potential transpiration is:

$$ET_{c\ act} = ET_r \cdot K_{cb} \cdot K_s + K_e \tag{2}$$

where ET_r is the evapotranspiration of a reference crop (mm day^{-1}), K_{cb} is a basal crop-specific coefficient, K_s is a stress coefficient that accounts for the decrease in plant water demand due to restricted transpiration, and K_e accounts for soil evaporation from precipitation or irrigation. The soil evaporation coefficient (K_e) under drip irrigation was assumed to be negligible in this study. A value for K_s has been estimated from the relationship between percent available soil water (PASW) and the management allowed soil water deficit (MAD) (Allen et al., 1998) or as an asymptotic function of PASW (Jensen et al. 1970). The PASW is calculated as:

$$PASW = 100 \cdot \left[\frac{\theta - \theta_{pwp}}{\theta_{fc} - \theta_{pwp}}\right] \cdot D_{rz} \tag{3}$$

where θ is current soil water content, θ_{fc} is soil water content (%) at field capacity, θ_{pwp} is soil water content (%) at permanent wilting point, and D_{rz} is effective rooting depth (m). The equations proposed by Allen et al. (1998) to estimate K_s are:

$$K_s = 1 \qquad PASW \geq MAD \tag{4}$$

$$K_s = \frac{PASW}{100 - MAD} \qquad PASW \leq MAD$$

where MAD is a soil water content (%) below which a crop begins to experience a water stress and transpiration is reduced. If $ET_{c\ act}$ is different than 5 mm day^{-1} then MAD can be adjusted as a function of $ET_{c\ act}$. For wine grapes, MAD has a suggested value of 35 to 45% (Allen et al., 1998). A value of 45% for MAD was assumed for analysis in this study. The equation proposed by Jensen et al. (1970) to estimate K_s (Colaizzi et al., 2003) is:

$$K_s = \frac{ln[100 - PASW + 1]}{ln[101]} \tag{5}$$

Both approaches for estimating K_s are empirical and require knowledge of vine soil water availability (θ, θ_{fc}, θ_{pwp}, D_{rz}), which can be challenging due to the spatial heterogeneity issues previously discussed.

A value for K_s has also been indirectly estimated from the CWSI (Colaizzi et al., 2003) and from the ratio of T_{canopy} to T_{LL} (Bausch et al., 2011). In both studies, T_{canopy} in relation to T_{LL} and/or T_{UL} was used to estimate K_s, $ET_{c\ act}$ and soil water availability. The relationship proposed by Colaizzi et al. (2003) can be expressed as:

$$CWSI = 1 - \frac{ET_{c\ act}}{ET_{cp}} \tag{6}$$

where ET_{cp} represents crop evapotranspiration under the same climatic conditions in the absence of transpiration limiting soil water availability (K_s=1). This relationship indicates that CWSI = 0 when soil water is not limiting ($ET_{c\ act} = ET_{cp}$) and CWSI = 1 when crop evapotranspiration is zero due to root zone soil water depletion to permanent wilting point. Substituting equation 2 for the numerator and denominator of the right side of equation 6 (K_e=0) with a value of K_s = 1 in the denominator (ET_{cp}) results in the relationship:

$$CWSI = 1 - K_s \tag{7}$$

indicating that there is a relationship between the CWSI and soil water content such as that given by equations 4 and 5 or a similar crop specific relationship.

The CWSI has been of limited use with wine grapes due to the practical difficulty of determining values for T_{LL} and T_{UL} while simultaneously measuring T_{canopy} (Jones et al., 2002). Approaches that have been used to estimate T_{LL} include energy balance equations (Sepúlveda-Reyes et al., 2016; Möller et al., 2007) natural or artificial reference surfaces (Sepúlveda-Reyes et al., 2016; Pou et al., 2014; Möller et al., 2007), and the difference in temperature between T_{canopy} and air relative to evaporative demand (Bellvert et al., 2015; Idso et al., 1981). A constant value relative to air temperature has been used to estimate a value for T_{UL} (Möller et al., 2007; King and Shellie, 2016).

King and Shellie (2016) predicted T_{LL} values for the wine grape cultivars Syrah and Malbec using a neural network (NN) model developed from cultivar-specific datasets of measured well-watered vine canopy temperature and environmental variables – solar radiation, air temperature, relative humidity and wind speed. They also estimated T_{UL} as air temperature plus a constant of 15 ˚C based on the cumulative probability of measured canopy temperature minus air temperature for the study conditions. They showed good correlation of calculated daily average CWSI over a 2 hr period about solar noon with irrigation and precipitation events and amounts. The relationship of the CWSI to other methods of evaluating vine water stress was not evaluated. Given that a vine daily CWSI can be calculated for wine grape, its relation to other common vine water stress measurements and usefulness for irrigation management has not been evaluated. The objective of this study was to evaluate the relationships between the CWSI, midday leaf water potential and soil water content in two cultivars of wine grape to develop an understanding of how a daily average CWSI can be used as a management tool to increase irrigation precision.

Methods and Materials

Equipment to measure vine canopy temperature, climatic conditions, and soil water content were installed at four sites in three, above-ground-drip irrigated commercial vineyards in southwestern Idaho on June 28th, 2017. Vine canopy temperature was measured using two infrared radiometers (SI-121 Infrared radiometer; Apogee Instruments, Logan, UT) on two vines separated by at least 5 m. The radiometers were positioned approximately 15 to 30 cm above recent fully expanded sunlit leaves located at the top of the vine canopy and pointed northerly at approximately 45˚ from nadir with the center of field of view aimed at the center of sunlight leaves. The measured canopy area received full sunlight exposure during midday and the radiometers were periodically checked and adjusted as necessary to ensure the field of view concentrated on recently fully expanded, sunlit leaves located on the top of the vine canopy. Environmental parameters; wind speed (034B wind sensor; Met One Instruments, Inc., Grant Pass, OR), air temperature, relative humidity (HMP50 temperature and humidity probe, Campbell Scientific, Logan, UT), and solar radiation (SP-110 pyranometer; Apogee Instruments, Logan, UT) were measured with instruments installed directly above the vine row within 15 m of the infrared radiometers. Soil water content was measured to a depth of 1.2 m in 10 cm depth increments using a Sentek Drill and Drop probe (Sentek Sensor Technologies, Stepney SA, AU) installed in the same vine row within 15 m of the infrared radiometers. The manufacturers calibration of each Drill and Drop probe was used in this study. Canopy temperature and climatic parameters were measured every minute, averaged over a 15-minute period and stored on a data logger (CR6, Campbell Scientific, Inc. Logan, UT). Soil water content was measured every 30 min and stored on the same data logger. The wine grape cultivars Malbec (MB) and Chardonnay (CH) monitored in each of two vineyards are hereafter referred to as MB1, MB2, CH1 and CH2. The upper and lower limits of volumetric soil water content (assumed field capacity θ_{fc} and permanent wilting point θ_{pwp}, respectively) were estimated in 10 cm increments at each site according to the maximum and minimum values measured throughout the season. When no soil drying was apparent, particularly at deeper depths, the value for θ_{pwp} was estimated as half the θ_{fc} value. Irrigation amounts were measured using a tipping bucket rain gauge (RainWise, Inc., Trenton, ME) under a single drip line emitter with irrigation amounts recorded as 15-minute totals.

Cultivar specific neural network models were used to estimate T_{LL} with the four measured climatic variables as model inputs (King and Shellie, 2016). The upper temperature threshold (T_{UL}) was estimated as air temperature plus 14 ˚C for area climatic conditions based on results reported by King and Shellie (2016). Daily CWSI was calculated as the average of 15-minute CWSI values from 13:00 to 15:00 MDT. The CWSI values were calculated in real time by the data logger and stored. Select measured and calculated parameters were made available real-time to vineyard managers on a website hosted by the data logger via cell phone modem. Irrigation decisions were made solely by the vineyard manager, each of which had access to real time values for daily CWSI and soil moisture content.

Vine water status was monitored weekly throughout berry development by measuring leaf water potential at midday (Ψ_{md}) using a pressure chamber (model 610; PMS Instruments, Corvallis, OR) following the method of Turner (1988) as described by Shellie (2006). Two, fully expanded, sunlit leaves were measured on each vine monitored with infrared radiometers.

Results and Discussion

The influence of irrigation events and amounts on daily CWSI for the cultivar Chardonnay at the second commercial vineyard site (CH2) is displayed graphically in Fig. 1. The daily CWSI values were very responsive to irrigation events. The CWSI value rapidly decreased during and following an irrigation event. Larger irrigation amounts resulted in larger declines in daily average CWSI values and vice versa. When irrigation depths were decreased from August 14 through September 1st, daily average CWSI values were the greatest and decreased following irrigation to a lesser degree. When an irrigation event was skipped between July 25th and August 1st, average daily CWSI continued to increase and rapidly declined to near zero with the relatively large irrigation depth on August 2nd. Common irrigation practice by the vineyard manager (personal communication) for study site CH2 is to withhold irrigation until approximately July 1st to develop soil water stress early in berry development and then maintain a mild severity of water stress throughout veraison by applying about 70% of estimated $ET_{c\ act}$ and limiting soil water content deficit to 50% total available water over a 0.9 m soil depth based on neutron probe weekly soil water monitoring.

At the CH2 study site, the measured soil water content at 10 cm increments to a depth of 60 cm is presented in Fig. 2. Active water infiltration and root extraction was apparent only within the 0 to 40 cm soil depth. Soil water deeper than 40 cm was not used to fulfill vine $ET_{c\ act}$ because there was no depletion of soil water below 40 cm during the season. The soil water content from 70 to 120 cm soil depth at the CH2 study site is presented in Fig. 3. The slow gradual decline in soil moisture at depths below 70 cm was negligible and likely due to drainage from 2016 fall irrigation to replenish root zone soil water and winter precipitation. Study site MB2, which was at the same commercial vineyard as study site CH2, also had a limited 40 cm root zone to supply water for vine $ET_{c\ act}$ (data not shown). Study site MB1, which had a much coarser textured soil, had an active root zone of 90 cm to supply water for vine $ET_{c\ act}$ (data not shown). The depth of active root zone at study site MB1 could not be identified because

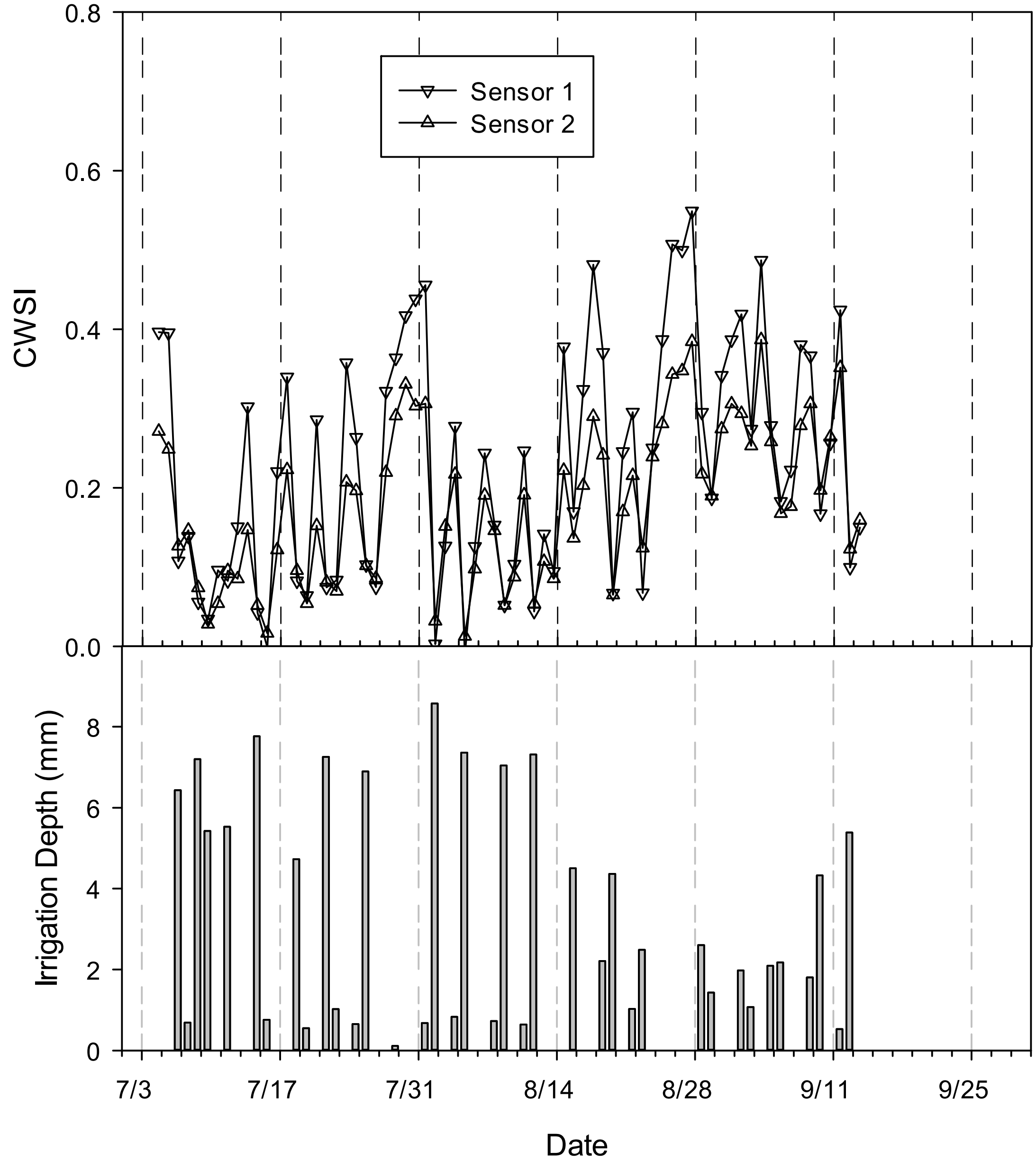

Figure 1. Daily crop water stress index (CWSI) values calculated as the average of 15-min CWSI values ±90 minutes of solar noon (top) and corresponding irrigation events and irrigation amounts per event (bottom) for the cultivar Chardonnay located in the second commercial vineyard site (CH2).

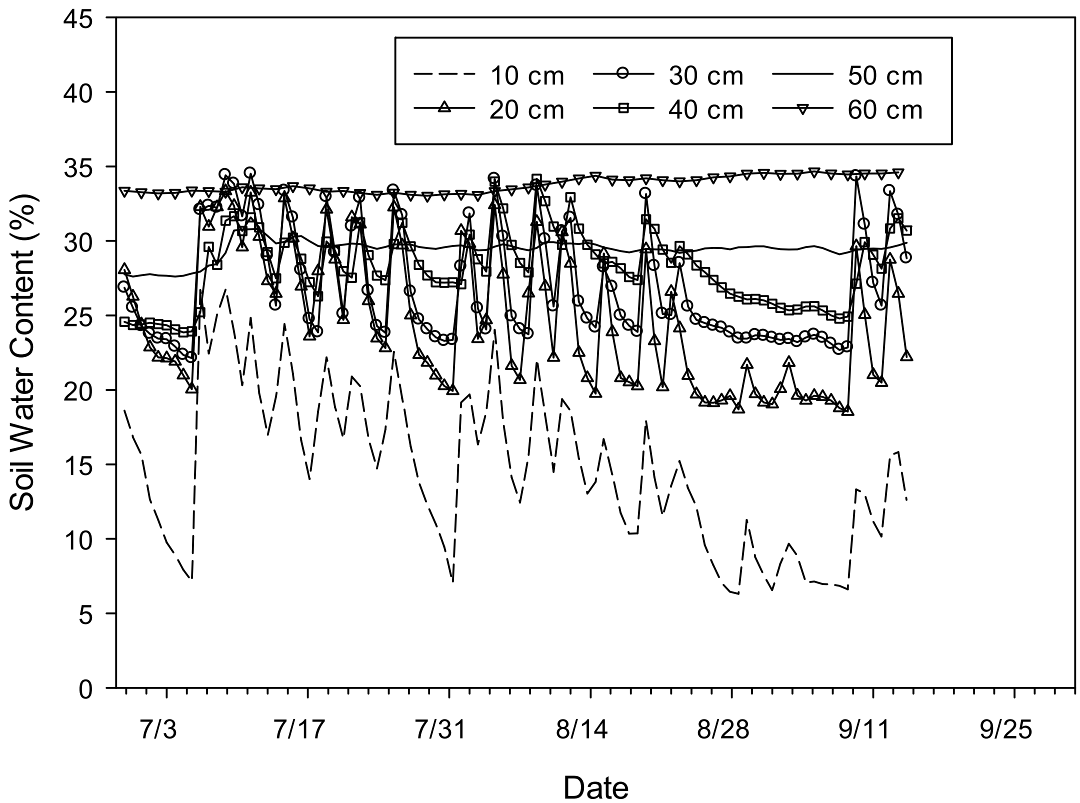

Figure 2. Volumetric soil water content measured at depths from 10 to 60 cm in plots of the cultivar Chardonnay located in the second commercial vineyard site (CH2).

the soil moisture sensor failed to detect a change in soil water content in the upper soil layers (< 20 cm). This may have been due to placement of the sensor relative to the drip irrigation emitters.

The estimated values for θ_{fc} and θ_{pwp} that were used to compute percent available soil water (PASW) for the silt loam textured soil at study site CH2, are listed in Table 1. Available soil water throughout the season for the 40-cm root zone at site CH2 (Fig 4) ranged from 23 to 95%. The wide range in available soil water was the result of the limited 40 cm root zone, high evapotranspiration demand, and approximate 4-day irrigation interval.

The relationship between the CWSI and PASW measured daily at 14:30 MST throughout the season at study site CH2 is presented in Fig. 5. The CWSI increased as PASW decreased, in accordance with equations 4 through 7. Also presented in Fig. 5 is the empirical relationships between PASW and the CWSI when the value of K_s in equation 7 is estimated using equation 4 (denoted as FAO K_s) and equation 5 (denoted as Jensen K_s). Visually, the empirical equation of Jensen et al. (1970) (eqn. 5, Jensen K_s) provided a better fit to the data than the FAO K_s piece-wise linear relationship (eqn. 4). Evaluation of each K_s equation fit to the measured data resulted in a mean square error (MSE) value for the Jensen K_s

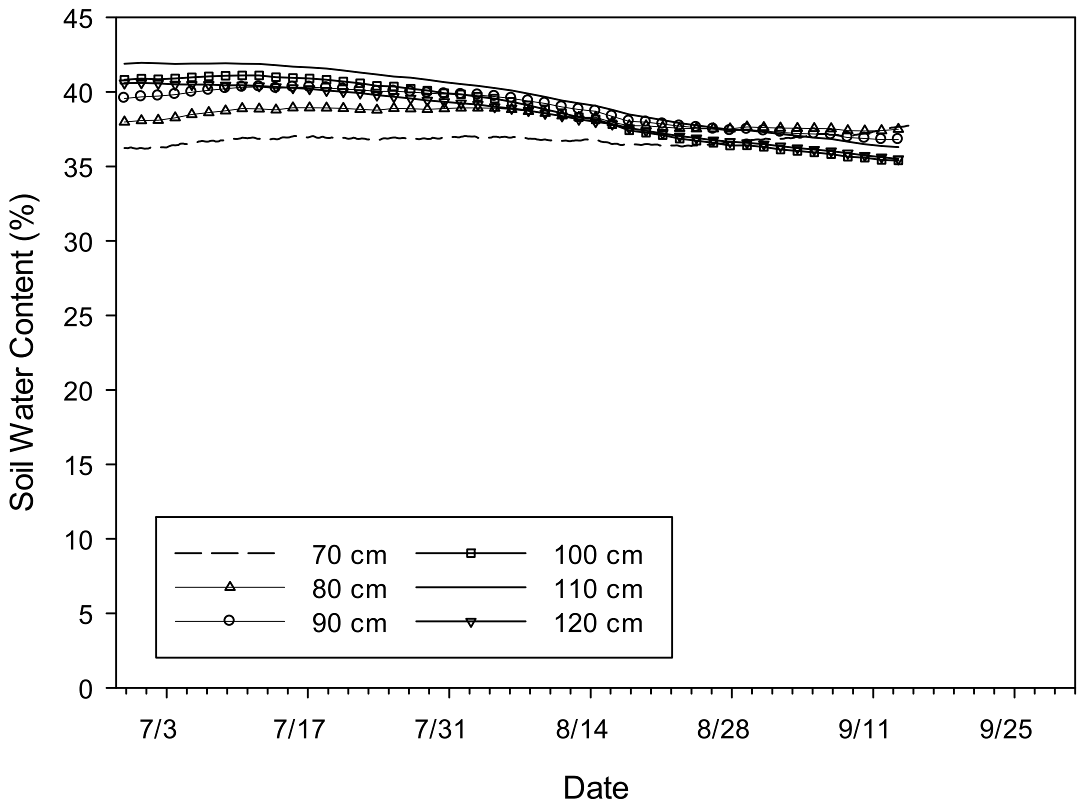

Figure 3. Volumetric soil water content measured at depths from 70 to 120 cm in plots of the cultivar Chardonnay located in the second commercial vineyard site (CH2).

Table 1. Soil volumetric water content (%) at field capacity and permanent wilting point used to calculate percent available soil water (PASW) in a field plot of the cultivar Chardonnay located at the second commercial vineyard site (CH2) in southwestern Idaho.

	Soil Depth (cm)											
	10	20	30	40	50	60	70	80	90	100	110	120
Field Capacity	28	35	34	34	34	34	37	39	41	41	42	42
Permanent Wilting Point	7	17	17	17	17	17	17	18	20	20	20	20

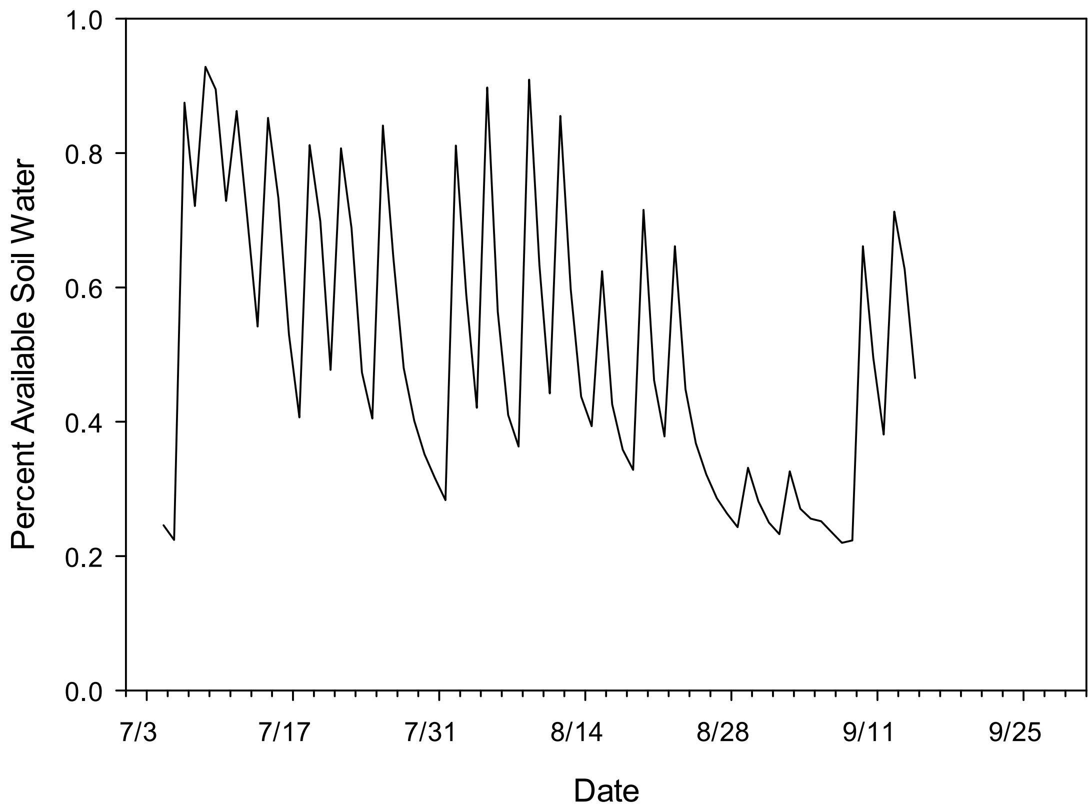

Figure 4. Estimated percent available soil water in the 0-40 cm soil depth in plots of the cultivar Chardonnay located in the second commercial vineyard site (CH2).

of 0.22 and 0.27 for the FAO K_s equation, indicating that the Jensen et al. (1970) equation provided a better fit to the measured data. The relationship between the CWSI and PASW for site MB2 presented in Fig. 6 also shows that the CWSI increased as PASW decreased. The empirical relationship of Jensen et al. (1970) (eqn. 5) visually fit the measured data better than the FAO K_s relationship (eqn. 4). Evaluation of each K_s equation fit to the measured data resulted in a mean square error (MSE) value for the Jensen K_s of 0.08 and 0.20 for the FAO K_s equation, indicating that the Jensen et al. (1970) equation provided a much better fit to the measured data. The relationship between CWSI and PASW for site MB1 is presented in Fig. 7. At the MB1 site, the CWSI increased exponentially as PASW approached zero. Evaluation of each equation fit to the measured data resulted in a MSE value for the Jensen K_s of 0.12 and 0.32 for the FAO K_s equation, indicating that the Jensen et al. (1970) equation provided a much better fit to the measured data. The data for the study sites MB1, MB2 and CH2 are presented collectively in Fig. 8. Again, the Jensen et al. (1970) equation for K_s provided a better fit to the measured relationship between CWSI and PASW having a MSE of 0.14 the MSE of 0.27 for the FAO K_s equation.

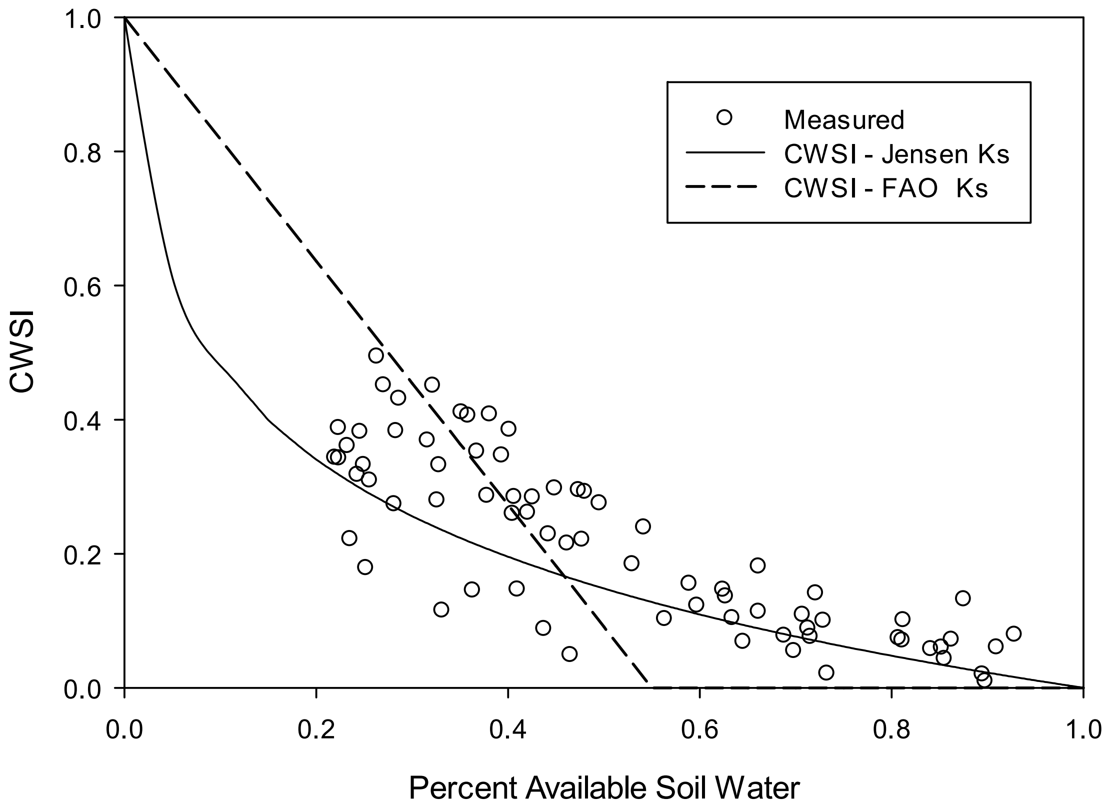

Figure 5. Relationship between crop water stress index (CWSI) computed based on average measured canopy temperature from 14:15 to 14:30 MDT and percent available soil water in the 0-40 cm soil depth based on soil water contents measured at 14:30 MDT in plots of the cultivar Chardonnay located in the second commercial vineyard site (CH2).

There are several sources of inherent variability in the relationship between the CWSI and PASW presented in Figs. 5 through 8. The calculations of the CWSI and PASW required estimation of equation parameters T_{LL}, T_{UL}, θ, θ_{fc}, θ_{pwp}, and D_{rz} with a level of uncertainty that could account for some of the scatter in the relationship. A single spatial measurement of soil water content was used to estimate PASW when it is well-known that the distribution of soil moisture and roots in the active root zone area of a grapevine is spatially very heterogeneous. At the beginning of an irrigation event, the decrease in vine canopy temperature occurs sooner and is faster than the increase in PASW. This can lead to different calculated values of the CWSI for a given value of PASW. It can also create hysteresis in the relationship between the CWSI and PASW if the soil is in the process of wetting or drying. Measured vine canopy temperature can fluctuate quickly due to variable solar radiation resulting from partly cloudy skies. The CWSI values in this study were calculated regardless of climatic conditions such as clouds and/or rainfall. The neural network models used to estimate T_{LL} also introduces a level of uncertainty in calculated CWSI values. Given the plethora of potential sources of error, it is quite

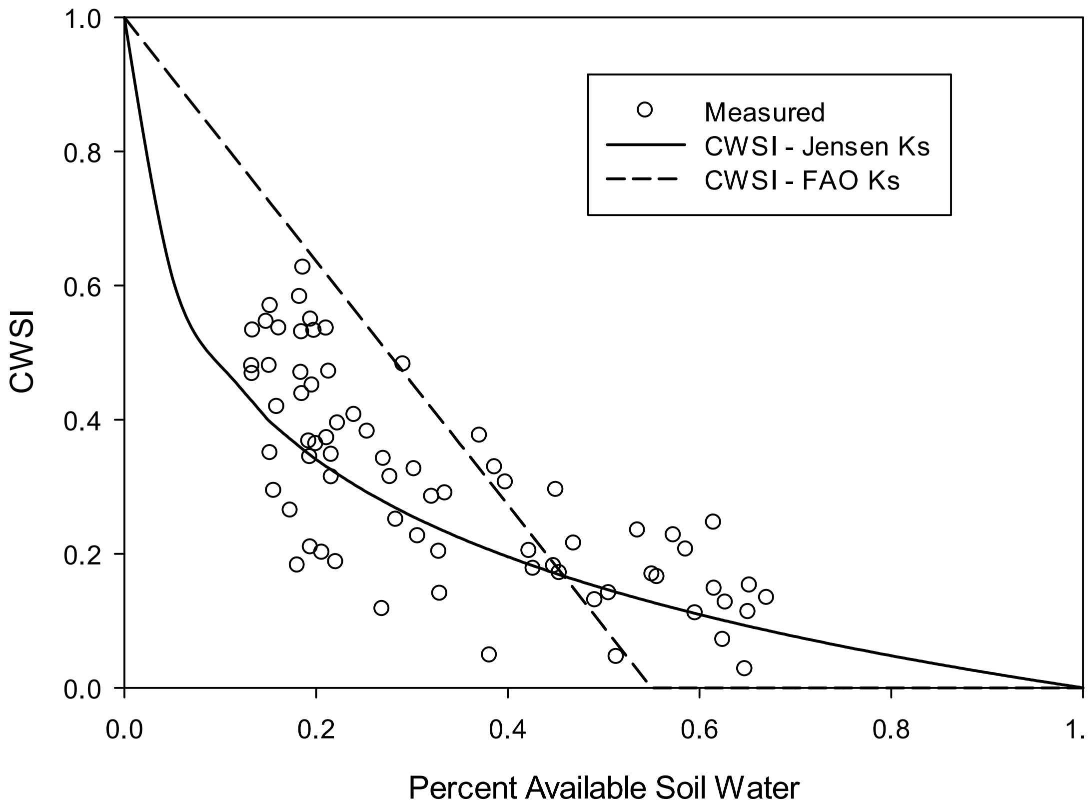

Figure 6. Relationship between crop water stress index (CWSI) computed based on average measured canopy temperature from 14:15 to 14:30 MDT and percent available soil water in the 0-40 cm soil depth based on soil water contents measured at 14:30 MDT in plots of the cultivar Malbec located in the second commercial vineyard site (MB2).

amazing that the relationship between the CWSI and PASW is defined to the degree seen in Figs 5 through 8. Despite this variability, the K_s equation proposed by Jensen et al. (1970) represented the relationship between the CWSI and PASW better than that of Allen et al. (1998).

The relationship between CWSI and Ψ_{md} is presented in Fig. 9. There was a significant ($p \leq 0.05$) linear relationship between the CWSI and Ψ_{md} showing that the CWSI increased as Ψ_{md} decreased. However, the low R^2 value of 0.21 indicates that there was a large amount of unexplained variability in the relationship. This large amount of variability could be attributed to operator differences (Williams et al. 2012) since the Ψ_{md} measurements were collected by several different personnel throughout the growing season.

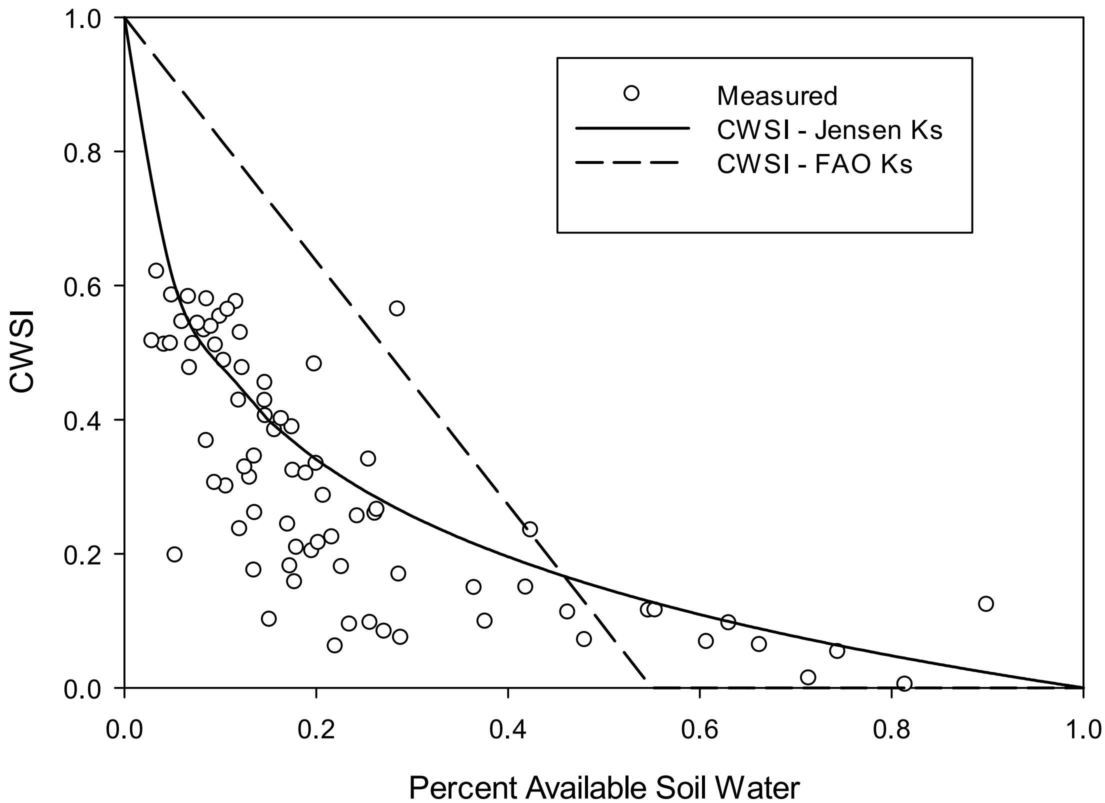

Figure 7. Relationship between crop water stress index (CWSI) computed based on average measured canopy temperature from 14:15 to 14:30 MDT and percent available soil water in the 0-90 cm soil depth based on soil water contents measured at 14:30 MDT in plots of the cultivar Malbec located in the first commercial vineyard site (MB1).

Conclusions

In this study, canopy temperature, air temperature, solar radiation, relative humidity, wind speed, soil profile water content and irrigation times and irrigation amounts were continuously monitored at four study sites located in three commercial vineyards in southwestern Idaho. A daily average CWSI was calculated using measured parameters ±90 minutes of solar noon. Daily average CWSI was linked to soil water content through the water stress coefficient K_s that accounts for reduced vine transpiration when soil water is limited. This linkage demonstrates that the daily CWSI is a reliable indicator of vine water stress resulting from limited soil water. The equation proposed by Jensen et al. (1970) for estimating K_s provided a better representation of the relationship between daily average CWSI and PASW than the equation proposed by Allen et al (1998). The CWSI was better correlated with PASW than with Ψ_{md}. These results demonstrate that a daily CWSI is a reliable method for monitoring grapevine water status under changing soil moisture conditions. The relationship observed in this study between the CWSI and PASW suggests that the daily average CWSI could be used as an irrigation management tool for

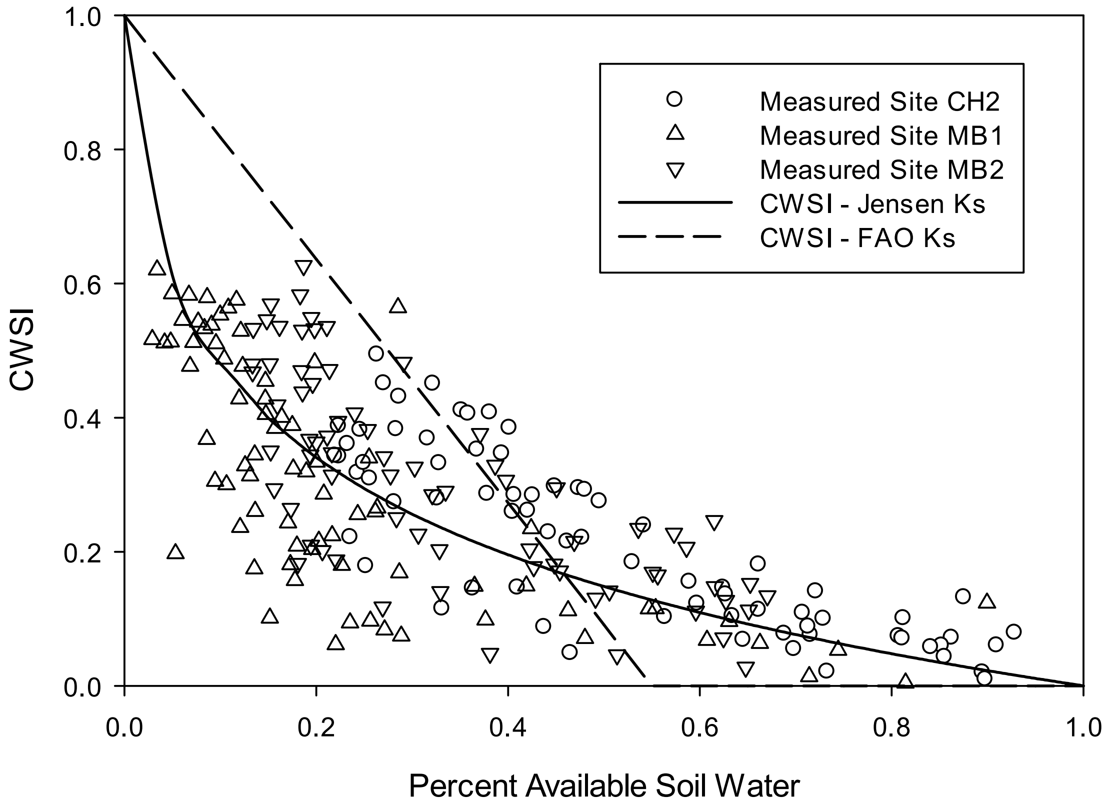

Figure 8. Relationship between crop water stress index (CWSI) computed based on average measured canopy temperature from 14:15 to 14:30 MDT and percent available soil water based on soil water contents measured at 14:30 MDT in plots of the cultivar Malbec at the first (MB1) and second (MB2) commercial vineyard and Chardonnay at the second commercial vineyard (CH2).

irrigation scheduling and potentially also for estimating the amount of water to supply during an irrigation event with further research.

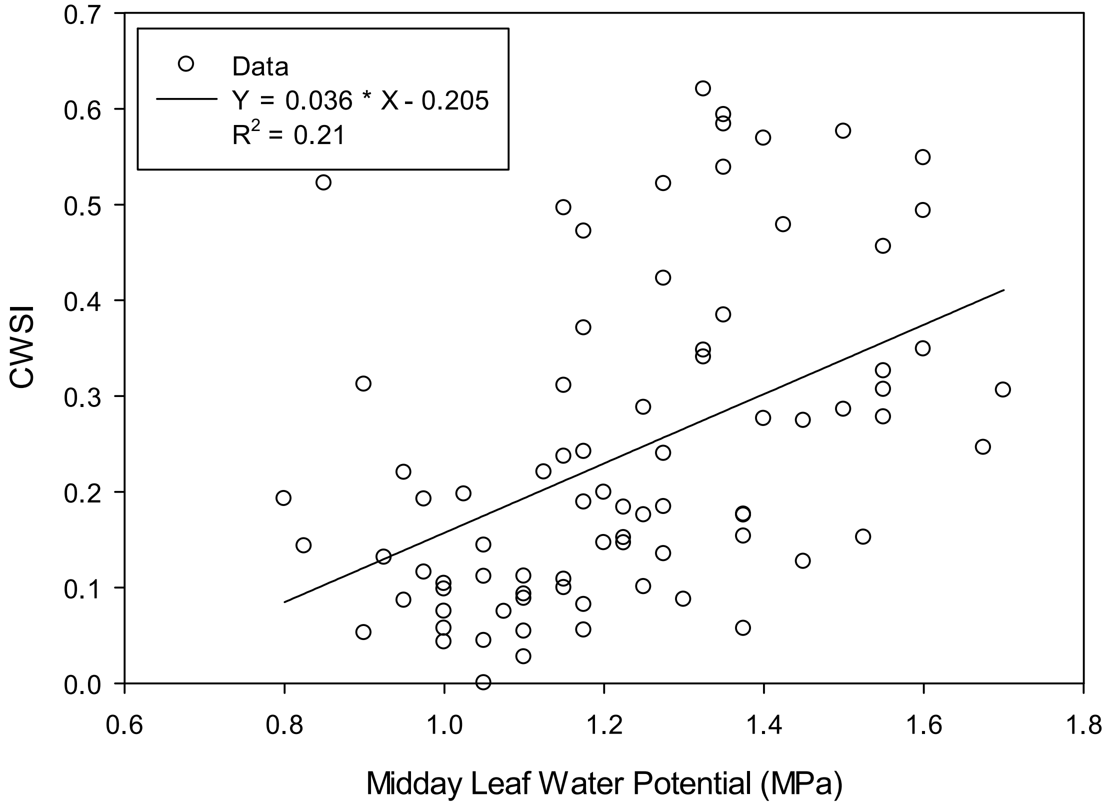

Figure 9. Relationship between the daily CWSI and midday leaf water potential of cultivars Malbec and Chardonnay measured throughout the 2017 growing season at four sites in three commercial vineyards in southwestern Idaho.

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