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RESEARCH ARTICLE

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Monitoring water status in apple trees using a sensitive morning crop water stress index*

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Abstract

The crop water stress index (CWSI) has shown to be a good indicator of water status in fruit trees. Conventional CWSI measured over solar noon is widely used to monitor plant water status. This study compared the theoretical CWSI averaged over morning hours, $CWSI_{mo}$, and over solar noon hours, $CWSI_{md}$, of apple trees. This study also assessed their sensitivity to the changes in soil water status (soil water deficit [SWD, %] and soil water potential [SWP, kPa]) at different root zone depths. Four different types of commercial and experimental apple orchards with different characteristics growing under semi-arid conditions in Washington State, United States, were chosen to assess $CWSI_{mo}$ against $CWSI_{md}$ sensitivity to soil water status. In some of these locations, soil water status ranged from fully watered to severely stressed (low water deficit to high water deficit). Ground-based thermal and microclimate measurements were recorded continuously at 10-s intervals and acquired for the 15-min average on a daily basis throughout the study period. The linear relationship between SWD and $CWSI_{mo}$ at the effective root zone depth (average of 0–150 mm and 0–460 mm) resulted in a slightly higher correlation (R^2 = 0.42–0.64, p < .001) compared to the traditional $CWSI_{md}$ (R^2 = 0.32–0.60, p < 0.001). The correlation between $CWSI_{mo}$ and SWP (R^2 = 0.38–0.69, p < 0.001) was found to be larger than the correlation between $CWSI_{mo}$ and SWD, while SWP was less correlated with $CWSI_{md}$ (R^2 = 0.33–0.55, p < 0.001). Interestingly, a better relationship between soil water status and both $CWSI_{mo}$ and $CWSI_{md}$ was observed using a nadir view orientation thermal measurement. The $CWSI_{mo}$ showed higher sensitivity to SWP than SWD.

KEYWORDS

crop water stress index, infrared thermometers orientation, soil water deficit, soil water potential, thermal sensing

* Surveillance de l'état de l'eau dans les pommiers à l'aide d'un indice de stress hydrique sensible des cultures matinales

RĖSUMĖ

L'indice de stress hydrique des cultures (CWSI) s'est révélé être un bon indicateur de l'état de l'eau des arbres fruitiers. Le CWSI conventionnel mesuré sur midi solaire est largement utilisé pour surveiller l'état de l'eau des plantes. Cette étude a comparé le CWSI théorique en moyenne sur les heures du matin, CWSImo, et sur les heures du midi solaire, CWSImd des pommiers. Cette étude a également évalué leur sensibilité aux changements de l'état hydrique du sol (déficit hydrique du sol, SWD,% et potentiel hydrique du sol, SWP, kPa) à différentes profondeurs de la zone racinaire. Quatre types différents de vergers de pommiers commerciaux et expérimentaux avec des caractéristiques différentes poussant dans des conditions semi-arides dans l'État de Washington, aux États-Unis, ont été choisis pour évaluer CWSImo par rapport à la sensibilité CWSImd à l'état de l'eau du sol. Dans certains de ces endroits, l'état de l'eau du sol variait de complètement arrosé à gravement stressé (déficit hydrique faible à déficit hydrique élevé). Les mesures thermiques et micro-climatiques au sol ont été enregistrées en continu à 10 secondes d'intervalle et acquises pendant la moyenne de 15 minutes sur une base quotidienne tout au long de la période d'étude. La relation linéaire entre SWD et CWSImo à la profondeur effective de la zone racinaire (moyenne de 0–150 mm et 0–460 mm) a abouti à une corrélation légèrement plus élevée (R^2 = 0,42-0,64, p < 0,001) par rapport au CWSImd traditionnel (R^2 = 0,32-0,60, p < 0,001). La corrélation entre CWSImo et SWP (R^2 = 0,38-0,69, p < 0,001) s'est avérée plus grande que la corrélation entre CWSImo et SWD, tandis que SWP était moins corrélée avec CWSImd (R^2 = 0,33-0,55, p < 0,001). Il est intéressant de noter qu'une meilleure relation entre l'état de l'eau du sol et à la fois CWSImo et CWSImd a été observée en utilisant une mesure thermique d'orientation en vue du nadir. Le CWSImo a montré une sensibilité au SWP plus élevée que le SWD.

MOTS CLÉS

Indice de stress hydrique des cultures, déficit hydrique du sol, potentiel hydrique du sol, détection thermique, orientation des thermomètres infrarouges

1 | INTRODUCTION

Agriculture is the largest consumer of fresh water. Due to the intensifying competition with other users from urban, industrial, and environmental sectors, the amount of water supplies to the agricultural sector is declining. Thus, to ensure a future of food security, improved approaches for irrigation scheduling are required. Irrigation scheduling enables growers to apply the exact amount of water that a plant needs to achieve the maximum use of soil moisture storage. Accurate irrigation scheduling increases irrigation efficiency and crop productivity.

Apples are the second most valuable fruit grown in the United States, 60% of which is grown in Washington State (Lynch, 2010). Growing apples in the semi-arid regions of the Pacific Northwest requires irrigation on a regular basis over the growing season. Most growers irrigate on a calendar basis instead of relying on actual water use estimations or soil water measurements. Poor irrigation management could result in water stress, diseases, apple bitter pit, and leaching of fertilizers. This significantly reduces fruit size, quality, and overall productivity. For maximizing water savings and increasing apple orchards' profitability, an irrigation strategy based on feedback from the trees themselves is crucial. Detecting stress earlier in the day also allows for more real-time response to that stress during the working hours of most agricultural workers.

Irrigation scheduling of orchard trees using soil–water balance with calculation of crop evapotranspiration (ET) based on reference ET and crop coefficients is a well-known approach. These crop coefficients are often chosen based on correlations with canopy size and height (Allen & Pereira, 2009). However, there is additional uncertainty due to planting density, tree architecture, row widths, and tree ages (Doltra *et al.,* 2007). Currently, this approach is being replaced by more accurate methodologies such as soil- and weather-based methods. These methods allow plants to match the water demand of their environment and keep this in balance with the water supply from the soil. The soil-based irrigation scheduling method is based on data from soil moisture or soil water potential sensors, while weather-based irrigation scheduling methods are based on soil–water balance and daily estimations of reference ET and an ET model. The ET models often used are the Penman–Monteith (Allen *et al.,* 1998) and Hargreaves (Hargreaves & Samani, 1985) methods.

Plant water status based on soil water measurements has long been used as a tool for irrigation scheduling. These measurements are not directly associated with the variables' environmental conditions. However, it can be used to represent the root zone despite the heterogeneity of soil (Campbell & Campbell, 1982; Charlesworth, 2005) if a representative site was chosen since irrigation scheduling does not require all the field soil information as the field is irrigated as a unit. Apple trees have a relatively shallow root zone which explains the relatively higher impact of climatic conditions on apple orchards' water status than of soil moisture (Lakso, 1994). This was the basis for developing thermal indices to detect plant water stress as an alternative to soil water monitoring-based methods (Tormann, 1986; Garrot *et al.,* 1993; Osroosh *et al.,* 2015b). The advantage of thermal indices is that the measurement is plant based. Plant-based methods provide irrigation timing without providing the amount of water to apply unlike soil-based methods. Combining this with the soil water measurement would allow us to have a better understanding of the actual water status in the plant.

Many indices have been developed to relate plant water stress signs to soil water status (Naor, 2008; Ihuoma & Madramootoo, 2017). The crop water stress index (CWSI) (Idso *et al.,* 1981; Jackson *et al.,* 1981) is a well-known index and uses normalized canopy temperature to detect crop stress. The CWSI is estimated using empirical (Idso *et al.,* 1981; Cohen *et al.,* 2005; Moller *et al.,* 2006), theoretical (Jackson *et al.,* 1988, 1981; Berni *et al.,* 2009; Gonzalez-Dugo *et al.,* 2014), and statistical estimations (Rud *et al.,* 2014; Cohen *et al.,* 2017). However, the empirical CWSI is easier to use due to the lower data requirements compared to the theoretical approaches (Maes & Steppe, 2012; Agam *et al.,* 2013).

The value of CWSI ranges from 0 for a non-stressed crop to 1 for an extremely stressed crop. However, in commercial orchards, there is a wide variety of canopy shapes, fruit sizes, and loads. This causes the proportional relationship between CWSI and stress level to be exposed to some measurement errors driven by heterogeneous tree canopies and varying fruit load and results in CWSI readings higher than zero, even when the trees are well watered (Fereres & Goldhamer, 2003: Lakso, 2003).

Numerous studies have employed infrared thermometry to assess the potential of CWSI measurements in different tree crops such as citrus (Stagno *et al.,* 2011; Gonzalez-Dugo *et al.,* 2014), peaches (Glenn *et al.,* 1989; Paltineanu *et al.,* 2009; Wang & Gartung, 2010; Bellvert *et al.,* 2016), olives (Ben-Gal *et al.,* 2009; Berni *et al.,* 2009; Akkuzu *et al.,* 2013; Bellvert *et al.,* 2016), pistachios (Testi *et al.,* 2008), grape (Moller *et al.,* 2006; Stoll & Jones, 2007; Bellvert *et al.,* 2014), and apples (Osroosh *et al.,* 2014, 2015a, 2015b, 2016b, 2016a).

The limitations of the empirical CWSI (Jackson *et al.,* 1988; Jones, 1999) are caused by neglecting climate factors such as wind speed and solar radiation and the need to create CWSI baselines applicable to different agroclimatic areas. The CWSI can be calculated using different methodologies. Cohen *et al.* (2017) summarize the methods for calculating CWSI, their limitations, and benefits. Many researchers have tried to improve the empirical CWSI for crop water stress monitoring and irrigation scheduling (Clawson *et al.,* 1989; Jones, 1999; Meron *et al.,* 2003; Leinonen & Jones, 2004; Moller *et al.,* 2006). For example, O'Shaughnessy *et al.* (2011, 2012) combined the time–temperature threshold (TTT) into a theoretical index (CWSI-TTT) used to automate irrigation of grain sorghum. However, they still experienced cases of under-irrigation associated with cloud cover or other micrometeorological incidents. The TTT method was also used to fully automate centre pivot irrigation scheduling (Peters & Evett, 2008). Osroosh *et al.* (2015b) introduced an adaptive irrigation-scheduling algorithm based on a theoretical CWSI specifically developed for apple trees. Their CWSI-based algorithm uses a dynamic threshold determined by following the CWSI trend.

With a few exceptions (O'Shaughnessy *et al.,* 2012; Osroosh *et al.,* 2016b), CWSI measurements at midday (1:00–3:00 p.m.) are the basis for monitoring crop water status. The main assumption here is that crop transpiration mainly responds to net radiation, which is maximum at midday. However, it has been shown that CWSI averaged over daylight hours, from 7:00 a.m. to 7:00 p.m. (Osroosh *et al.,* 2016b) is more reliable to detect water stress in fruit trees because it eliminates the effects of short microclimatological effects and intervals and yields a more stable index for irrigation scheduling. If CWSI is measured earlier in the day, this would keep trees at a well-watered status by applying an irrigation event if needed (Mohamed *et al.,* 2019).

The key objective of this research was to develop a more sensitive CWSI (CWSI averaged over morning hours, $CWSI_{mo}$) under different water stress levels. The specific objective was to investigate the relationships between CWSI and soil water status (soil water deficit [SWD], %) and soil water potential (SWP, kPa) at different root zone depths at four sites across Washington State to represent variability among the locations.

2 | MATERIALS AND METHODS

2.1 | Study areas

The study was carried out in four different commercial and experimental apple orchards that covered a wide variety of geographical locations. The orchards are located in Prosser, Royal City, Quincy, and George, WA. The sites in Prosser, Royal City, Quincy, and George, WA, will now be referred to as site 1, 2, 3, and 4, respectively. A detailed description and the condition of each site are shown in Table 1. The study areas have a semi-arid climate, short summer rain, and an average annual rainfall of 180–217 mm. Soil texture estimates were obtained from the Web Soil Survey (Natural Resources Conservation Service, NRCS). The soils were not affected by salt.

All the orchards were well developed. The soil water status ranged from fully watered (no SWD) conditions (i.e., the Prosser orchard) to severely stressed (high SWD) conditions (i.e., Royal City orchard). Site 4, in George, WA, was completely covered with shade cloth for sunburn protection. in site 1, Prosser, WA, there was almost no fruit due to alternate bearing (irregular crop load from year to year). This provided an opportunity to test the sensitivity and reliability of $CWSI_{mo}$ in detecting water status adequately because there was no concern of yield loss. There was a cooling system (overtree sprinkler irrigation system) in two orchards (sites 2 and 3) to prevent fruit sunburn. Harvesting dates ranged from end of August for orchards 2 and 3 and mid-October for orchard 4.

2.2 | Sensor setup

Ground-based soil-plant-weather monitoring stations included sensors such as soil water sensors, IRTs (for plant canopy temperature detection), and weather sensors. Monitoring stations (Figure 1) were mounted on aluminium poles. To ensure repeatable and precise monitoring of canopy temperature, three stations were placed at locations distant from each other in the orchard at ¼, ½, and ¾ of one single row. Each station included sensors as shown in (Figure 1) with only one weather station that was located halfway of the row. Each station was capable of monitoring two adjacent canopies, one located on the south and the other on the north. All the sensors were wired to a couple of Z6 dataloggers (model Em60G; Meter Group, Inc., Pullman, WA) on each station that recorded at 10-s intervals and stored 15-min averages. Sensors' wires were shielded using a white PVC casing. Data from these sensors was reported back to a decision support system (ZENTRA Cloud; Meter Group, Inc., Pullman, WA) capable of logging and visualizing data remotely.

TABLE 1 A detailed description of the study orchards

	0.27 ha	12.9 ha	13.8 ha	11.3 ha
Site area, location, and type	Lat: 46.2529687, Long: −119.7274735	Lat: 46.9179174, Long: −119.6524271	Lat: 47.2289958, Long: −119.9477452	Lat: 47.0905323, Long: −119.95511051
	Experimental	**Commercial**	**Commercial**	**Commercial**
Soil characteristics (at depth 483 mm)	Warden silt loam	Kennewick silt loam	Shano silt loam	Prosser very fine sandy loam
	$\theta_{FC} = 28.3\%$	$\theta_{FC} = 28.4\%$	$\theta_{FC} = 29\%$	$\theta_{FC} = 19\%$
	$\theta_{PWP} = 10\%$	$\theta_{PWP} = 10\%$	$\theta_{PWP} = 9\%$	$\theta_{PWP} = 8\%$
Irrigation system (lines × dripper)	Micro-sprinklers (4 × 0.508 m)	Drip laid on the ground (1.5 × 0.6 m)	Drip (2.4 × 0.6 m), dripline height (0.3 mm)	Drip laid on the ground (2.5 × 0.75 m)

Note: θ_{FC}: soil water content at field capacity.
θ_{PWP}: amount of water in soil that is unavailable to the plant (PWP, permanent wilting point).

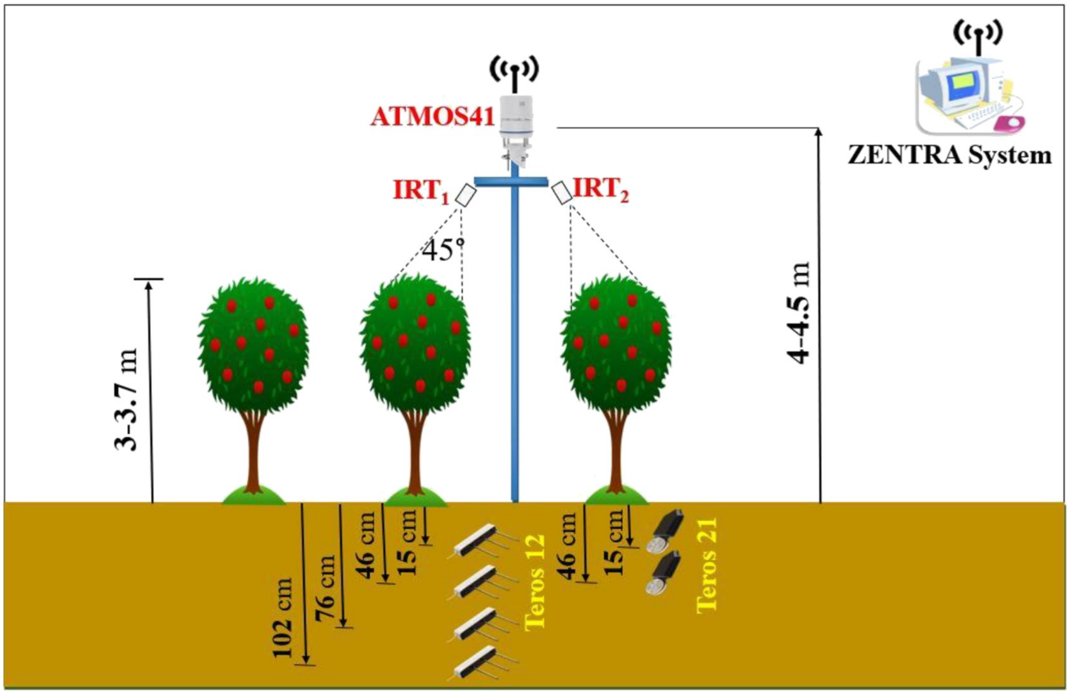

FIGURE 1 A simplified illustration of ground-based measurements using in-field sensors and a decision support system integrated with wireless sensor network. IRT, infrared thermometer [Colour figure can be viewed at wileyonlinelibrary.com]

2.2.1 | Thermal measurements

For each station, two IRTs (Model: SI-4H1; Apogee Instruments, Inc., Logan, Utah) with a field of view of 32° horizontal half-angle and 13° vertical half-angle, and a measurement range of −60°C to 110°C. IRT sensors were installed pointing downwards at approximately 45° angles at both the northern and southern sides of a tree to capture the temperature of the canopy. The heights of all the trees in each orchard was relatively uniform, with no shading from the neighbouring trees. An additional orientation of the IRTs was installed in the George orchard at nadir view angle. An illustration of the sensors' setup can be seen in Figure 1. The mounting distance was adjusted in a way that only the canopy was in the view of the IRT (no soil background inclusion) and such that when the trees reached their full canopy growth, the IRT still stayed out of the canopy. The average values of canopy temperature measurements from all the stations were then input into the CWSI model.

2.2.2 | Soil water status measurements

In order to continuously monitor soil water status in the orchards to assess the sensitivity of the morning crop water stress index to soil water status (deficit and potential) under different soil characteristics, volumetric soil water content (VWC) sensors (TEROS 12; Meter Group, Inc., Pullman, WA), with a volume of influence of 1,010 ml, a resolution of 0.001 m^3/m^3, and an accuracy from ±0.01 to 0.02 m^3/m^3 (±1–2% VWC) in any porous medium, were installed for each of the three stations in between two consecutive trees in the same row at four different depths (150, 460, 760, and 1,020 mm). The large number of sensors used was to cover the whole root zone depth and take the non-homogeneity of soil and soil water distribution into consideration. On the opposite side of the TEROS 12 installation location, and for each of the three stations, TEROS 21 (Meter Group, Inc., Pullman, WA) sensors with a measurement range of −9 to −2,000 kPa, a resolution of 0.1 kPa, and an accuracy of ±(10% of reading + 2 kPa) from −100 to −9 kPa were installed to monitor the soil water potential at ¼ and ¾ of the root zone depth (150 and 460 mm, respectively). TEROS 12 was calibrated using the standard factory calibration curve as the sensor was not soil type dependent (Kizito *et al.,* 2008). Each TEROS 21 sensor was calibrated individually from −10 to −80 kPa against an absolute suction reference (Meter Group Inc., 2020). SWD (%) was calculated as $\{([\theta_{FC} - \theta_{VWC}]/[\theta_{FC} - \theta_{PWP}]) \times 100\}$, where θ_{FC} is the soil water content at field capacity, θ_{VWC} is the measured volumetric soil water content at soil depth, and θ_{PWP} is the soil water content at permanent wilting point. The management allowable depletion (MAD), expressed in percent, was set for apple trees as 0.5 of the total available water (Allen *et al.,* 1998).

2.2.3 | In-field plant measurements

During the growing season of 2018, the stem water potential (Ψ_{stem}) was measured late in the morning (between 10:00 and 11:00 a.m.) and around solar noon (between 12:30 and 1:30 p.m.) with a pressure bomb (Model 1505D; PMS Instrument Co., Albany, OR) The accuracy of the readings was 0.5%–1% for 0–10,000 kPa. These measurements were taken twice per week from August 14 to September 18, 2018. Three shaded leaves were selected from the inner, lower section of tree canopies close to tree trunk and adjacent to the sensor stations (Turner & Long, 1980; McCutchan & Shackel, 1992). The leaves were enclosed in aluminium foil-covered plastic bags. The leaves were kept covered for approximately 60 min (Fulton *et al.,* 2001). Ψ_{stem} in the morning and at midday were measured for a total of three Ψ_{stem} sample readings per targeted canopy.

2.2.4 | Microclimatic measurements

Microclimate data were acquired over the growing season using the ATMOS 41 (METER Group, Inc., Pullman, WA) all-in-one weather station. Measurements taken included vapor pressure, relative humidity (RH), solar radiation, wind speed and direction, maximum wind gust, air temperature, and precipitation. ATMOS 41 was installed as a function of canopy height, so the tree vegetation is representative, and above the canopy surface at a height of 4 m above the ground surface. This distance of separation was far enough from the trees' canopies to not interfere with the measurements and close enough to accurately reflect the microclimate near the measurement. Research studies have shown that the CWSI is very sensitive to RH and air temperature measurements, and thus these parameters should be measured as close as possible to the canopies (Gardner *et al.,* 1992). Thus, one ATMOS 14 (Meter Group, Inc., Pullman, WA) sensor was installed on one of the stations that was located in the middle of the row and ended up between and above two consecutive trees and close to the canopies.

2.3 | Theoretical CWSI calculation

Theoretical CWSI (Idso *et al.,* 1981; Jackson *et al.,* 1981) was calculated by comparing the measured canopy and air temperature difference ($\Delta T_i = T_c - T_a$) with the upper limit of water-stressed baseline ΔT_y and the lower limit of non-water-stressed baseline ΔT_x:

$$\mathrm{CWSI} = \frac{\Delta T_i - \Delta T_x}{\Delta T_y - \Delta T_x}, \tag{1}$$

where ΔT_i is the difference between measured canopy (T_c) and air (T_a) temperatures, ΔT_y is the temperature difference between canopy and air for a non-transpiring canopy, ΔT_x is the temperature difference between canopy and air temperatures under a well-watered tree canopy (non-water-stressed baseline). ΔT_x was calculated according to Osroosh *et al.* (2015b) as follows:

$$\Delta T_x = Q\frac{1}{\gamma + u} - \frac{1}{\mathrm{atm}(\gamma + u)}\mathrm{VPD}, \tag{2}$$

where Q is the net radiation, atm is the atmospheric pressure, $u = \Delta/\mathrm{atm}$; Δ is the linear slope between saturation vapor pressure (e_s, kPa) and air temperature (T_a, C). VPD is the vapor pressure deficit, γ is a constant stated by Campbell & Norman (1998) similar to the psychrometric constant and can be calculated as follows:

$$\gamma = \frac{g_{Hr}C_p - m}{\lambda g_v}, \tag{3}$$

where $g_{Hr} = 2g_H$, and g_H is the boundary layer conductance to heat, $m = (3\alpha_L - 4)\varepsilon_a(C)\sigma T_a^3$, where T_a is the air temperature (K), α_L is absorptivity in the thermal waveband, C_p is the heat capacity of air ($\mathrm{mol}^{-1}\mathrm{C}^{-1}$), λ is the latent heat of vaporization ($\mathrm{J\ mol}^{-1}$), atm is the atmospheric pressure, and VPD was calculated after Idso *et al.* (1981) as follows:

$$\mathrm{VPD} = e_s - e_a, \tag{4}$$

where e_s is the saturated vapor pressure (kPa), $e_a = e_s\mathrm{RH}$ is the actual vapor pressure of air (kPa). g_{va} is the vapor conductance ($\mathrm{mol\ m^{-2}\ s^{-1}}$) and calculates as follows (Osroosh *et al.,* 2015b):

$$g_{va} = a\frac{(\mathrm{atm})Q}{\lambda \mathrm{VPD}}, \tag{5}$$

where a is the calibration adjustment coefficient.

The upper limit, ΔTy, was calculated for a non-transpiring canopy (Osroosh *et al.,* 2015b):

$$\Delta T_y = \frac{R_n}{g_{Hr}C_p - m}. \tag{6}$$

This study was conducted starting from the beginning to the late growing season, but the data analysis was performed from mid- to late-season (June 6, 2018 to September 21, 2018) to avoid erroneous canopy temperature measurements during the early season due to incomplete canopy growth since the higher soil background temperatures can create significant errors (O'Shaughnessy *et al.,* 2012). Differences between the canopy and air temperatures (ΔT_i), upper limit (ΔT_x) and lower limit (ΔT_y) for all the orchards in the morning and midday hours (Figure 2) were calculated using a calibration coefficient ($a = 8$) which is used to calculate the vapor conductance (Osroosh *et al.,* 2015b). This calibration coefficient is required for the theoretical non-water-stressed baseline that is described in Equation 1. The main statistical measures used were a linear regression between soil water status and CWSI and analysis of variance ($p = 0.05$).

3 | RESULTS AND DISCUSSION

3.1 | Morning and midday canopy and air temperature difference

A marked difference in (ΔT_i) clearly exists between the non-stressed orchard (Prosser) (Figure 2a,b) and the stressed orchard (George) (Figure 2g,h) or the severely stressed orchard (Royal City) (Figure 2c,d) in both morning and midday hours. For the non-stressed orchard, ΔT_i was lower than for the stressed orchard. This can be explained by the fact that the plant tends to close stomata due to reduced water availability (Fuchs *et al.,* 1967), indicating the different functionality of stomata. Closed

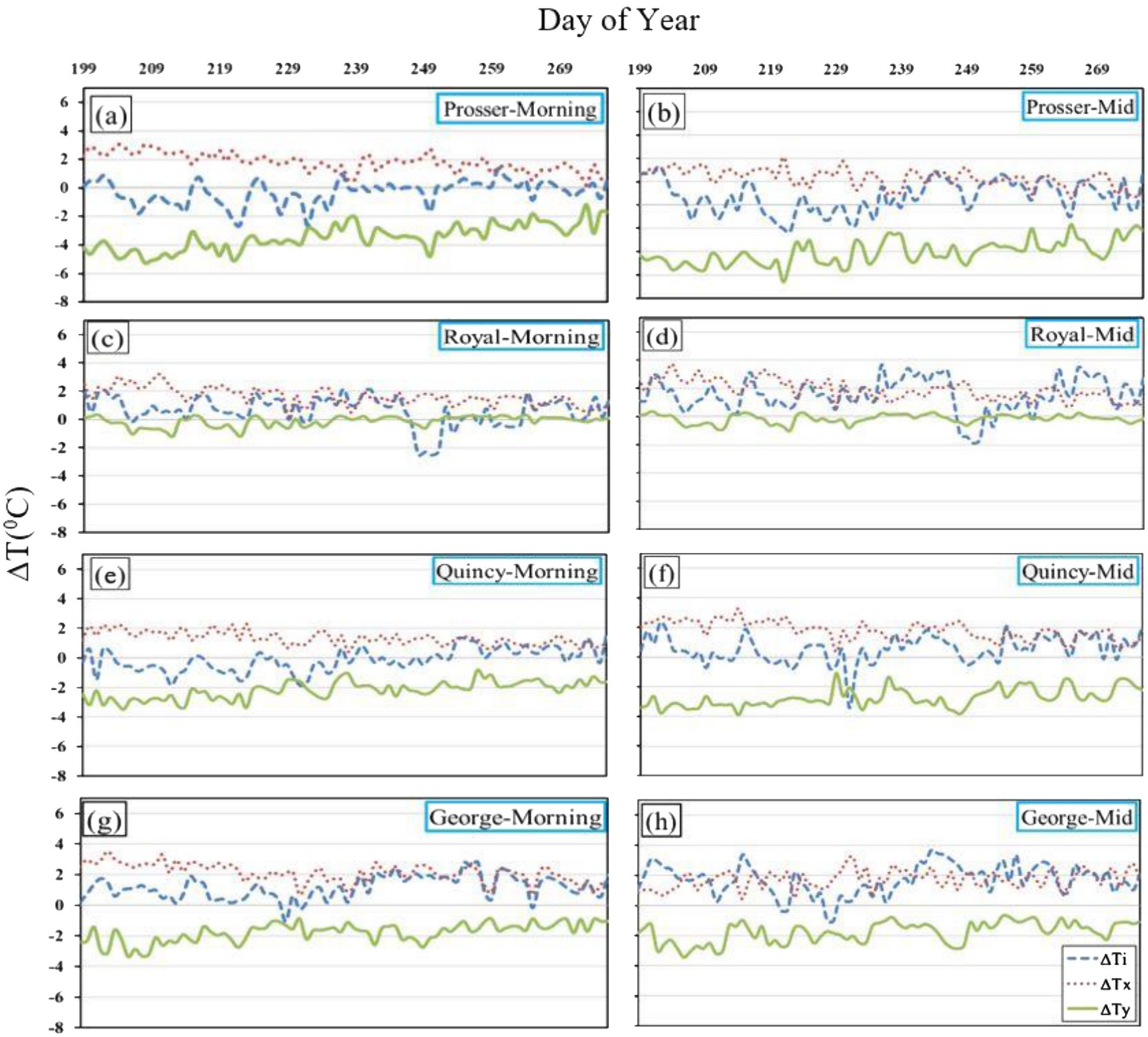

FIGURE 2 Seasonal fluctuations of measured canopy and air temperature difference (ΔT_i), the temperature difference between canopy and air temperatures under a well-watered tree canopy (ΔT_x [upper limit], non-water-stressed baseline), and the temperature difference between canopy and air for a non-transpiring canopy (ΔT_y [lower limit]) in the morning and midday hours over the study period [Colour figure can be viewed at wileyonlinelibrary.com]

stomata consequently increase canopy temperature relative to air temperature (Blonquist *et al.,* 2009; Pou *et al.,* 2014), which mainly occurs in the midday hours in apple trees (Tőkei & Dunkel, 2005). In general, ΔT_i was lower in the morning than the midday hours for both non-stressed and stressed orchards.

Similar to the findings of Testi *et al.* (2008), Gonzalez-Dugo *et al.* (2014), and Osroosh *et al.* (2016b), all well-watered orchards maintained an average difference between canopy and air temperature below 0°C for many days. However, a different pattern was noticed in the stressed orchards (Royal City and George), where differences were considerably higher than 0°C. In most of the orchards, ΔT_i reached its highest value on the late-season days for both morning and middays hours.

3.2 | Variation of morning and midday CWSI

Here, the study compared the conventional CWSI measured at midday (1:00–3:00 p.m.), $CWSI_{md}$, with CWSI measured late in the morning (10:00–11:00 a.m.), $CWSI_{mo}$. Figure 3b shows that the stressed $CWSI_{mo}$ values from Royal City were somewhat higher than those of the well-watered in Prosser (Figure 3a). Moreover, on many days, non-stressed orchards showed a constant level of CWSI. CWSI in both the morning and at midday followed the same trend. However, $CWSI_{md}$ values were much higher than $CWSI_{mo}$. This can be explained by the increase in stomatal conductance in the morning hours and the consequently higher transpiration rate in the morning. On the other hand, CWSI in the Royal City orchard had much variability in the late season, and CWSI values decreased dramatically indicating high water stress status in plants. This was due to a failure in the irrigation system. Fruit load has a great effect on the stomatal conductance of apple leaves, which is decreased by a reduction in load (Wünsche *et al.,* 2000; Lakso, 2003; Reyes *et al.,* 2006). The higher values of $CWSI_{md}$ in the Prosser orchard were mostly caused by no fruit load and accordingly led to a smaller difference in canopy and air temperature (Osroosh *et al.,* 2016b).

3.3 | Relationships between ψ_{stem} and CWSI

The relationship between ψ_{stem} and CWSI was investigated in one orchard (Prosser). The morning and midday ψ_{stem} and relationships between ψ_{stem} and CWSI in the morning and at midday are shown in Figures 4a and 4b, respectively. As expected, a significant difference was noticeable between ψ_{stem} measured in the morning and at midday. Averaged morning ψ_{stem} values ranged between −0.38 and −0.59 MPa, while averaged midday ψ_{stem} values ranged from −0.51 to −0.68 MPa. On a humid day (RH = 41%, day of year = 239), the relative value of ψ_{stem} was the highest among the measured values. That is the day when the transpiration rate was

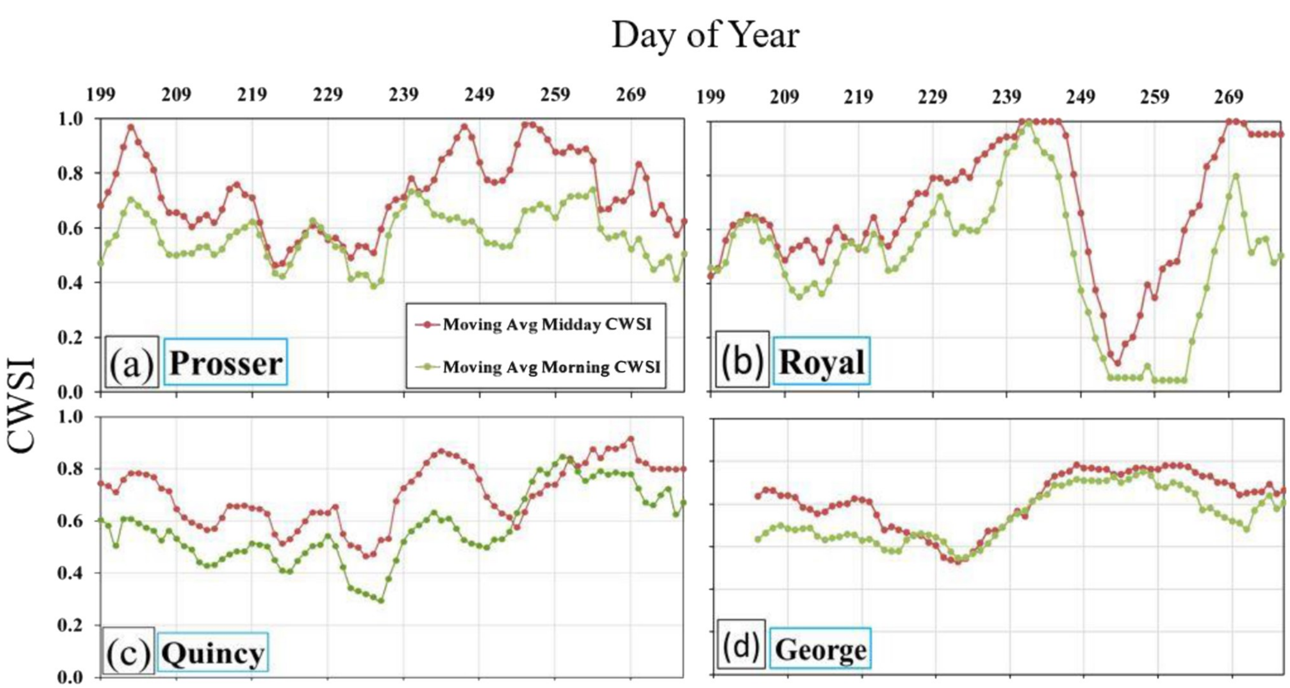

FIGURE 3 Moving average values of morning and midday CWSI during the study period. CWSI, crop water stress index

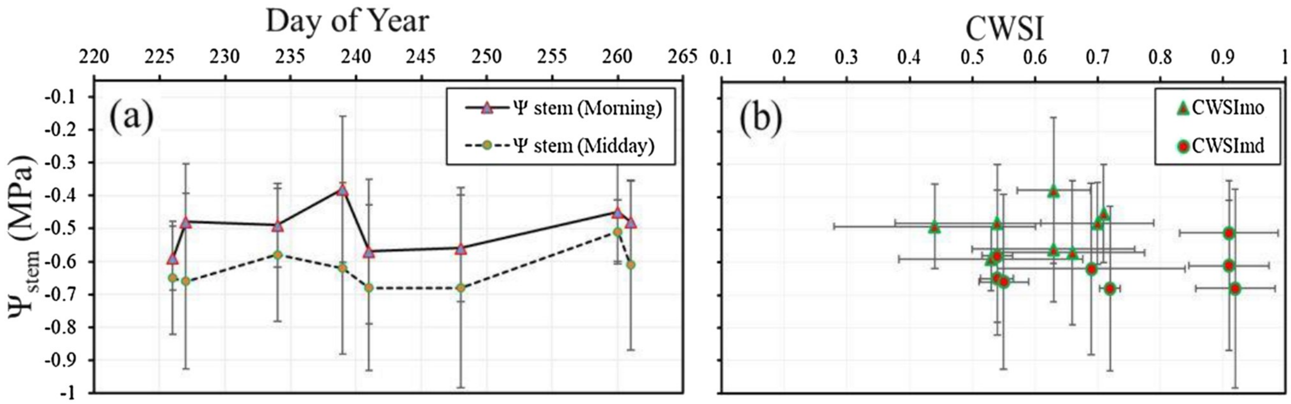

FIGURE 4 Morning and midday of stem water potential (ψ_{stem}) through the season (a). Relationships between ψ_{stem} (MPa) and CWSI in the morning and at midday (b). The error bars show the standard error of the mean. CWSI, crop water stress index; $CWSI_{mo}$, CWSI averaged over morning hours; $CWSI_{md}$, CWSI averaged over solar noon hours

low (Fereres & Goldhamer, 2003; Doltra *et al.,* 2007). In general, the values of ψ_{stem} were in agreement with the reference values reported for apple trees (Naor & Cohen, 2003). However, the results revealed that there was no significant relationship between CWSI and ψ_{stem}, which could be due to the small size of our dataset. The higher values of $CWSI_{mo}$ and $CWSI_{md}$ were corresponded to more negative ψ_{stem}. These variations of ψ_{stem} were mainly associated with climatic conditions (Abrisqueta *et al.,* 2015). Nevertheless, using leaf water potential for irrigation scheduling is laborious and uses few measurements to characterize large population of plants. So, CWSI would be desirable as a quick and real-time method (Idso *et al.,* 1981).

3.4 | Soil water status and CWSI sensitivity analysis

The soil water status obtained from the station's two sensors (TEROS 12 and TEROS 21) at depths 150 and 460 mm, which is the effective root depth, were averaged. The detailed day-to-day fluctuation in the averaged soil moisture values in the effective root zone obtained from the TEROS 12 and 21 sensors are shown in Figure 5. SWD reading differences from the TEROS 12 sensors in all sites were 0.1%–1.6%, while the SWP reading differences from TEROS 21 were 0.1–1.7 kPa. The data acquired from the sensors showed that the soil water status ranged from no soil water stress to high SWD. For

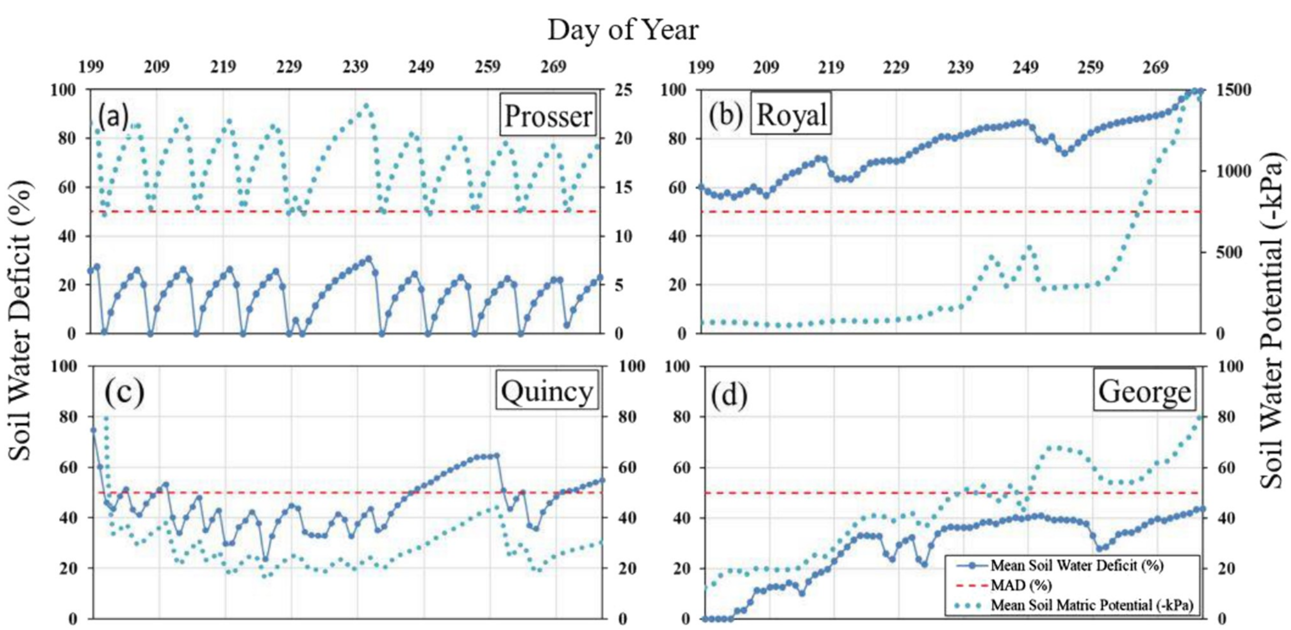

FIGURE 5 Average of soil water status course (deficit [%] and potential [-kPa]) at effective root depth in the different orchards over study period. The secondary y-axis of each plot is tailored to the corresponding observed soil water potential of each site. MAD, management allowable depletion

example, in the Prosser orchard, the trees did not experience a high water deficit over the study period (Figure 5a), and SWD ranged from 0% to 30.5% and SWP from −12 to −23 kPa. On the other hand, during the study period, the Royal City orchard trees were severely stressed (Figure 5b). The SWD ranged from 56% to 99.4% corresponding to relative SWP values that were much higher and ranged from −56 to −1,500 kPa. The higher variability of CWSI in the stressed orchard (Royal City, Figure 3b) was due to an irrigation system failure leading to under-irrigation. SWD was below the MAD in the Prosser and George orchards (Figures 5a and 5d). In the Royal City, Quincy, and George orchards (Figures 4b, 4c, and 4d), both SWD and SWP were relatively high in their values due to the water cutting off to avoid mud during harvest at the end of the season. This also explains the higher CWSI values in the late season (Figures 3b, 3c, and 3d).

The detailed coefficient of determination values of the repetitive linear regression between soil water status at different root zone depths and CWSI are shown in Table 2. In the regression analysis, some data points in the Royal City orchard were neglected in the calculation when the irrigation system failed. $CWSI_{mo}$ was found to be more correlated to soil water status than $CWSI_{md}$. For instance, a linear regression analysis of the total SWD (%) at the effective root zone depth (average of depths 150 mm and 460 mm) against relative $CWSI_{mo}$ yielded a slightly higher correlation with R^2 = 0.42–0.64 (p < 0.001; Figure 6a), while a weaker correlation was found between $CWSI_{md}$ and SWD with R^2 = 0.32–0.60 (p < 0.001; Figure 6b). A similar linear regression between soil water potential (-kPa) and $CWSI_{mo}$ resulted in a fairly good correlation, with R^2 = 0.38–0.69 (p < 0.001; Figure 6c), while it was less correlated with $CWSI_{md}$ with R^2 = 0.33–0.51 (p < 0.001; Figure 6d), indicating that $CWSI_{mo}$ is a more predictive indicator of water status in the apple root zone to a depth of 150 mm and 460 mm. Both $CWSI_{mo}$ and $CWSI_{md}$ exhibited variable correlations for both SWD and soil water potential for soil depths of 720 mm and 1,070 mm (Table 2).

3.5 | IRTs orientation and soil water status relationship

Variations in the CWSI measurement are a function of the measured canopy temperature. These variations depend on the angle from which the IRT is monitoring the canopy. Thus, to investigate the impact of the IRT orientation on the CWSI calculation and the relationship with soil water status, an additional IRT orientation

TABLE 2 Coefficient of determination values of linear regression analysis between soil water status (soil water deficit [SWD] and soil matric potential [SMP]) and crop water stress index (CWSI)

Orchard		Prosser				Royal City				Quincy				George			
Soil water status		SWD		SMP		SWD		SMP		SWD		SMP		SWD		SMP	
CWSI		Mo	Md	Mo	Md	Mo	Md	Mo	Md	Mo	Md	Mo	Md	Mo	Md	Mo	Md
Depth (mm)	0–150	0.29	0.24	0.42	0.33	0.15	0.14	0.52	0.47	0.34	0.36	0.48	0.29	0.22	0.12	0.55	0.38
	0–460	0.74	0.64	0.79	0.62	0.67	0.62	0.15	0.10	0.40	0.30	0.19	0.29	0.72	0.61	0.87	0.71
	Effective depth (average of 0–150 and 0–460)	0.52	0.45	0.63	0.50	0.64	0.60	0.52	0.55	0.42	0.37	0.38	0.35	0.45	0.32	0.69	0.51
	0–760	0.79	0.70			0.74	0.75			0.12	0.16			0.81	0.65	0.85	0.71
	0–1,020	0.74	0.68			0.77	0.79			0.03	0.05						

Abbreviations: Md, average midday hours; Mo, average morning hours

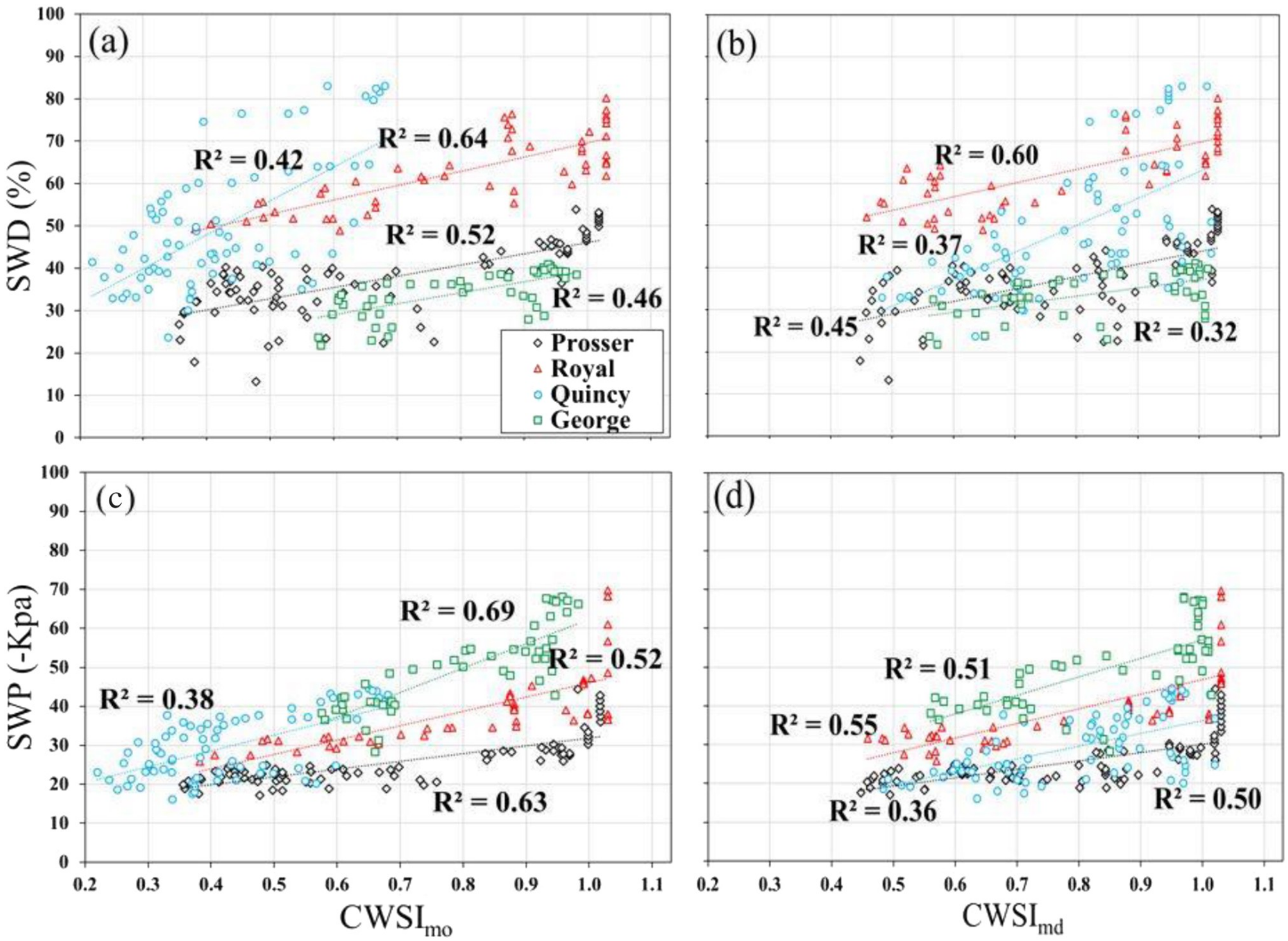

FIGURE 6 Linear regressions between SWD in different study locations and $CWSI_{mo}$ (a) and $CWSI_{md}$ (b). Linear relationships between soil water potential SWP and $CWSI_{mo}$ (c) and $CWSI_{md}$ (d). $CWSI_{md}$, crop water stress index averaged over solar noon hours; $CWSI_{mo}$, CWSI averaged over morning hours; SWD, soil water deficit

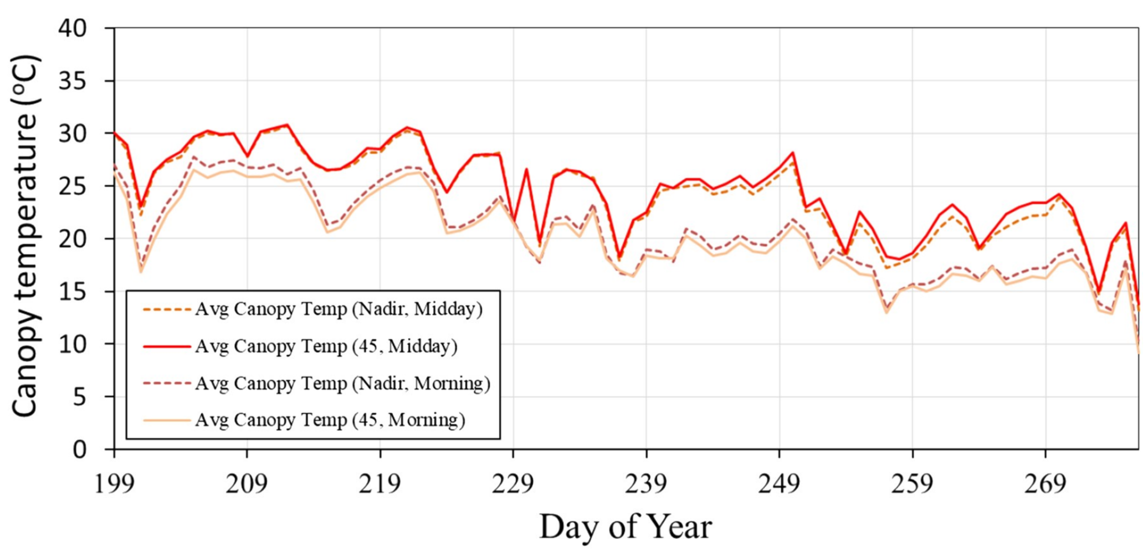

FIGURE 7 Average canopy temperature at nadir view and 45° for midday and morning hours in Quincy orchard

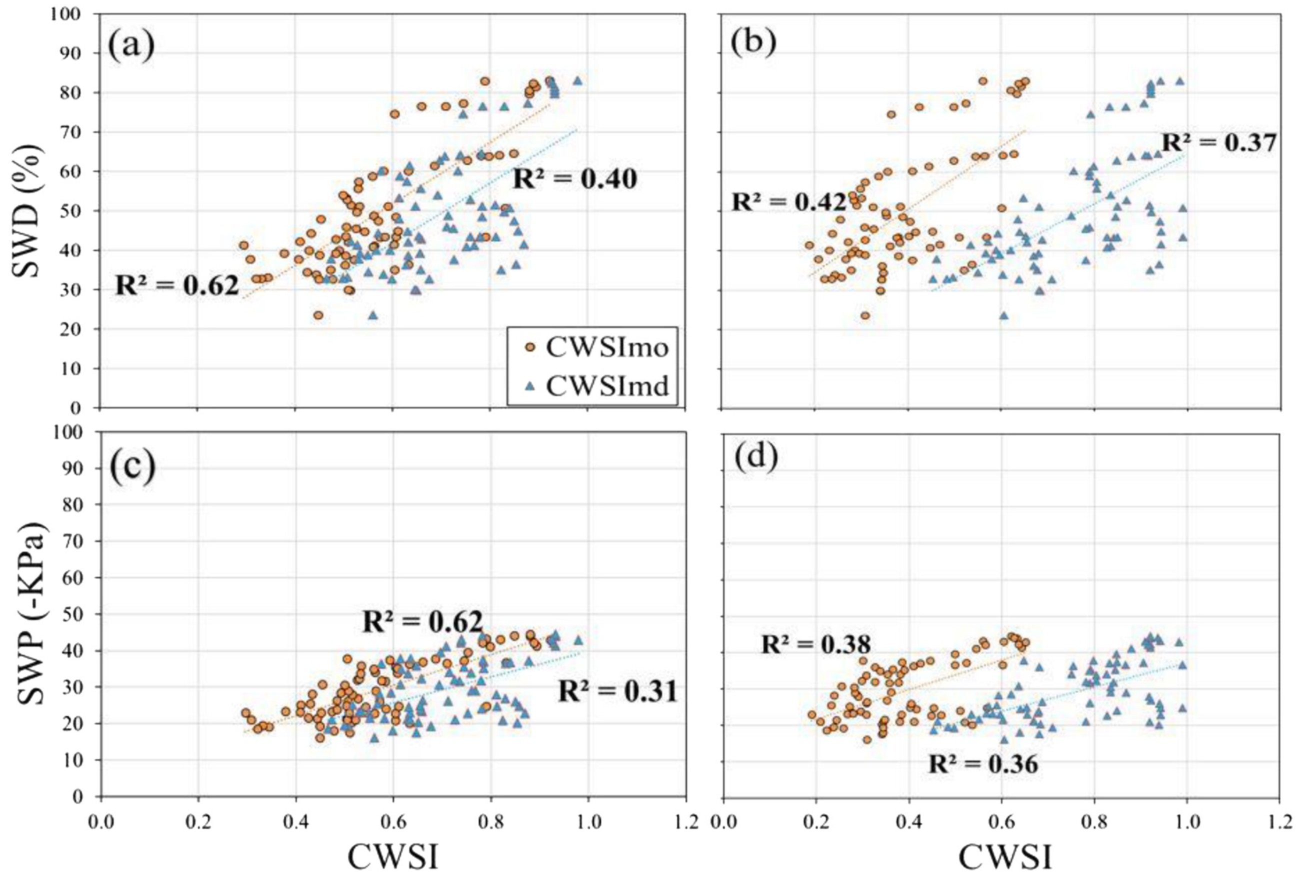

FIGURE 8 Linear regressions between SWD and CWSI (Quincy orchard) calculated using nadir view (a) and 45° angle view (b). Linear relationships between SWP and CWSI calculated using nadir view (c) and using 45° angle view (d). CWSI, crop water stress index; SWD, soil water deficit; SWP, soil water potential

(nadir view) was installed at the Quincy orchard. The average canopy temperature at nadir and 45° viewed in the morning and midday hours is shown in Figure 7. In general, the readings of canopy temperature at nadir and 45° view followed nearly the same trend. The CWSI values calculated using nadir view measurements resulted in slightly higher correlations with both SWD and SWP measurements than those calculated using the 45° orientation from both sides and averaging (Figure 8b,d). The $CWSI_{mo}$ values calculated using nadir view measurements were better correlated with both SWD and SWP than those with $CWSI_{md}$. For the effective depth, on the one hand, $CWSI_{mo}$ calculated using nadir view orientation yielded a good correlation with SWD (R^2 = 0.62, p < 0.001; Figure 8a), while the correlation between $CWSI_{md}$ and SWD was slightly less (R^2 = 0.40, p < 0.001; Figure 8a). A similar linear regression between SWP and $CWSI_{mo}$ resulted in a fairly high correlation (R^2 = 0.62, p < 0.001; Figure 8c), while SWP was less correlated with $CWSI_{md}$ (R^2 = 0.30, p < 0.001; Figure 8). On the other hand, $CWSI_{mo}$ calculated using 45° orientation yielded a lower correlation with SWD (R^2 = 0.42, p < 0.001; Figure 8b), while the correlation between $CWSI_{md}$ and SWD was much less correlated (R^2 = 0.37, p < 0.001; Figure 8b). Moreover, the linear regression between SWP and $CWSI_{mo}$ for 45° orientation resulted in a worse correlation (R^2 = 0.38, p < 0.001; Figure 8d), while SWP was much less correlated with $CWSI_{md}$ (R^2 = 0.36, p < 0.001; Figure 8d).

4 | CONCLUSIONS

In the present study, we investigated the effectiveness of CWSI values calculated using a theoretical model and averaged over the late morning hours ($CWSI_{mo}$) as an indicator of water status in apple trees in the semi-arid region of Washington. Soil moisture sensors were used to continuously monitor soil water status. Based on the results from all the study orchards, theoretical morning CWSI was more sensitive to soil water status availability. In general, the correlation between the CWSI and soil water potential was slightly higher than the correlation between the CWSI and SWD. Linear correlations between the CWSI and soil water status showed that $CWSI_{mo}$ is slightly more responsive to changes in soil moisture than $CWSI_{md}$. Both $CWSI_{mo}$ and $CWSI_{md}$ calculated using the nadir view orientation were slightly more correlated with soil water measurements than those calculated using a 45° angle orientation of the tree from two opposite sides and averaged. $CWSI_{mo}$ shows promise to estimate plant water stress status in apple trees. $CWSI_{mo}$ would allow for detecting water stress earlier in the day and eventually maintaining trees at a well-watered status by applying an irrigation event if needed. In addition, this study emphasized and highlighted the feasibility of $CWSI_{mo}$ under a no-fruit (alternate bearing) scenario, in an orchard with cloth shading, and variable water stress options. Finally, further research needs to be conducted to analyse the robustness and sensitivity of the relationship between the CWSI and soil water status and orchard productivity.

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