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Automatic irrigation scheduling of apple trees using theoretical crop water stress index with an innovative dynamic threshold

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ABSTRACT

An adaptive scheduling algorithm relying on a theoretical crop water stress index (CWSI) was developed to automatically irrigate apple trees. Unlike the traditional CWSI algorithm where the threshold is a constant value, in the present approach the threshold is dynamically determined by following the CWSI trend. A previous work on the energy budget analysis of a single apple leaf provided the base for calculating lower and upper boundaries of CWSI. To test the feasibility of the algorithm, it was applied to the thermal and meteorological data collected during the 2007 and 2008 growing seasons. A computer-based wireless control system was also developed to automatically schedule irrigations in three plots of apple trees in the 2013 growing season. In a small scale field experiment, two treatments were compared: (1) automatic irrigation using the new algorithm (CWSI-DT) and (2) irrigation scheduling based on weekly readings of neutron probe (NP). The soil water deficit under the CWSI-DT treatment was maintained within the well-watered range with no signs of over or under irrigation. This was better than the results in the NP treatment where there were occasions of under irrigation. Midday canopy and air temperature difference (ΔT_m) exhibited a close agreement with midday stem water potential (Ψ_{stem}; $R^2 = 0.63$, $p < 0.01$). Normalizing ΔT_m in the form of CWSI resulted in a much higher correlation between midday CWSI and midday Ψ_{stem} ($R^2 = 0.91$, $p < 0.0001$) suggesting CWSI as a reliable indicator of apple trees water status. The automatic control system running the new CWSI-DT algorithm was able to avoid over-irrigation under humid and cool weather conditions, and adapted itself to the changing conditions of the apple trees. The results of this study were promising in terms of using ground-based thermal sensing for automatic irrigation scheduling of sparse, discontinuous apple trees.

1. Introduction

To increase profit and water savings, and agricultural sustainability, and to reduce environmental impacts, implementation of appropriate irrigation scheduling methods is necessary (Smith et al., 1996). The use of infrared thermometry and most recently thermal imagery, along with a number of supplemental environmental measurements, have been introduced as an alternative approach to soil- or weather-based methods of irrigation scheduling (Jackson et al., 1977; Wanjura et al., 1995; Cohen et al., 2005). Various thermal methods/indices have been developed such as the crop water stress index (theoretical CWSI; Jackson et al., 1981; Jackson et al., 1988; empirical CWSI: Idso et al., 1981) and time–temperature threshold (TTT; Wanjura et al., 1992; Wanjura et al., 1995). CWSI is defined by a comparison of the actual canopy and air temperature difference with an upper water-stressed base line (WSBL) and a lower non-water-stressed baseline (NWSBL) which are calculated using empirical or theoretical approaches.

Compared to row crops, relatively less work is reported in the literature on the irrigation scheduling or water stress detection in tree crops using CWSI. Thermal methods in the form of empirical CWSI have been studied in different trees such as pistachios (Testi et al., 2008), peaches (Wang and Gartung, 2010; Paltineanu et al., 2013), olives (Agam et al., 2013a; Berni et al., 2009; Akkuzu et al., 2013), and citrus trees (Gonzalez-Dugoa et al., 2014). Osroosh et al. (2015) developed theoretical NWSBLs for apple trees based on the energy balance of a single leaf.

CWSI is traditionally calculated at or averaged over a short period of time around solar noon. This is the time when the crop is exposed to the maximum level of solar radiation and believed to

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show signs of stress. However, this calculation approach makes the index susceptible to many unwanted transitional weather related factors such as dust or passing clouds (O'Shaughnessy et al., 2012; Agam et al., 2013b). Analytical models respond to different meteorological conditions including high wind speed and radiation change which are not accounted for in empirical models (Jackson et al., 1988; Jones, 1999). The dynamic conditions of the tree canopies including fruit load change, a change in optical/thermal properties and light interception due to vegetative growth, or short term oscillations of canopy temperature (Casadesus et al., 2012; Gonzalez-Dugoa et al., 2014; Osroosh et al., 2015) disconnect between soil water content and CWSI response.

The conventional CWSI-based approach of irrigation scheduling used a static/fixed threshold above which an irrigation signal is triggered. This is while the threshold actually changes as a function of many factors including weather conditions and crop growth. This threshold is not easy to determine and might require field experiments with crops under full or deficit irrigation. The CWSI value for a crop under no stress is normally assumed to be zero (minimum CWSI), and for a severely stressed crop to be close to one (maximum CWSI; Jackson et al., 1981). While these assumptions might be true in the instance of homogeneous canopies of major row crops, it is not applicable to heterogeneous tree canopies. The interference of thermal radiation from the ground with canopy temperature readings, as well as the rough nature of the tree canopies can lead to smaller canopy and air temperature differences and consequently result in CWSI values greater than zero even in well-watered canopies (Fereres et al., 2012). On the other hand, the temperature of apple tree canopies increases as low fruit loads are reached because stomatal conductance is a function of load and reduces as the load decreases (Lakso, 2003). As a result, non-water stressed baselines are dependent on the load and might not reach zero in well-watered trees with no or very low load.

To date, the efforts have primarily concentrated on improving the empirical or theoretical methods of estimating the baselines (Clawson et al., 1989; Jones, 1999; Meron et al., 2003; Leinonen and Jones, 2004; Möller et al., 2007). This is while the common approach is still as basic as simple comparison of the midday CWSI with a predetermined crop and site specific threshold. In order to improve the performance of the CWSI algorithm as a trigger for automatic irrigation scheduling of grain sorghum, O'Shaughnessy et al. (2012) incorporated a time threshold (TT) into a theoretical index (CWSI-TT). They used CWSI-TT successfully to automate irrigations of grain sorghum in a semi-arid region. However, they still reported an under-irrigation problem caused by cloud cover and the impact of changing crop aspect on IRT measurements.

The main objective of this research was to develop and evaluate an adaptive CWSI-based irrigation algorithm with a dynamic threshold (CWSI-DT). The goal was to maintain the trees in a well-watered condition and to avoid over irrigation mainly due to erroneous irrigation signals on cool and humid days, caused by temporary weather conditions, and canopy growth.

2. Materials and methods

2.1. Study area

The field experiments were conducted in a Fuji apple orchard on the Roza Farm of the Washington State University Irrigated Agriculture Research and Extension Center near Prosser, WA, at the coordinates of latitude 46.26°N, longitude 119.74°W, and 360 m above sea level. The site was located in a semi-arid zone with almost no summer rains and an average annual precipitation of 217 mm. The site's soil was a shallow Warden Silt Loam, ~1-m deep with an impermeable rocky layer limiting soil depth to less than 0.6 m in some locations. The average volumetric water content at field capacity, θ_{FC}, was estimated in the field to be 32.5% (measured as drained soil water content after an irrigation event), and the value of the volumetric water content at permanent wilting point, θ_{PWP}, was assumed to be 13.8% (Saxton and Rawls, 2006). The trees were spaced 4 m (row spacing) by 2.5 m (tree spacing) apart in the orchard. In 2007 and 2008, they were irrigated with a micro-sprinkler irrigation system (Hurricane, NaanDanJain Irrigation Ltd., Post Naan, Israel) with water emitters of 27 L h^{-1} spaced at 2.5 m intervals. During the 2013 growing period, the orchard was irrigated with two lines of pressure compensating drip tubing laterals (~0.6 m apart) of in-line 2.0 L h^{-1} drippers (BlueLine® PC, The Toro Company, El Cajon, CA), spaced at 0.914 m intervals along laterals.

2.2. Treatments and experiment design

The proposed CWSI-DT algorithm as discussed later was initially applied to the data collected in field experiments in 2007 and 2008 where young, well-developed apple trees were fully-irrigated. A fully-watered status was assured by maintaining the soil water deficit within the management allowable depletion (MAD) for apple trees recommended by Allen et al. (1998) ($MAD = 50\%$ of total available water). The control algorithm was then used to automatically schedule irrigations in three plots in 2013 (CWSI-DT irrigation treatment) where the same apple trees that while healthy, for various reasons bore little or no fruit. Irrigation scheduling using neutron probe (NP) was also conducted in three similar plots (NP irrigation treatment). Soil moisture readings were made weekly and the soil was fully replenished to field capacity. The irrigation treatments (i.e. CWSI-DT and NP) were evaluated in a randomized complete block design (RCBD) with three replications/blocks (total of 6 plots).

2.3. Control system and automatic measurements

Real-time canopy temperature (T_c), relative humidity (RH), solar radiation (S_r), wind speed (u) and air temperature (T_a) were required field measurements for calculating theoretical CWSI (described later). To collect data and implement automatic irrigations, a wireless central control system including hardware and graphical user interface (GUI) was developed. The electronic hardware consisted of a centrally located 900 MHz spread-spectrum radio as master (RF401, Campbell Scientific, Logan, UT, USA) and six wireless sensor nodes as slaves. The master was connected to a laptop computer and the slaves to dataloggers located in the orchard. A sensor node was made up of a CR10(X) datalogger (Campbell Scientific, Logan, UT, USA) and all or some of the following sensors/components: (a) shielded air temperature sensors (Model 109, Campbell Scientific, Logan, UT, USA), (b) infrared thermometers (IRT/c.2: Type J, Exergen, Watertown, Mass.) with a field view of 35° and ±0.6 °C accuracy, and (c) latching solenoid valves (Irritrol, Riverside, CA) actuated by L298 dual H-bridge motor drive (Robotshop Inc., Mirabel, Quebec, Canada), and 900 MHz spread-spectrum radio (RF401, Campbell Scientific, Logan, UT, USA) to transmit data and receive control signal to/from the central control. All of the nodes were powered using batteries and 10 W solar panels (SYP105, Instapark Co., Santa Fe Springs, CA). The nodes took measurements from the field sensors and reported them to the control computer.

The GUI was developed in VB.Net (V.2010, Microsoft Inc., Redmond, WA). The GUI collected data from the sensor nodes, acquired real-time weather data from web, ran the adaptive irrigation algorithm, and automatically scheduled irrigation to the plots (three CWSI-DT and three NP plots). Weekly NP readings of soil water content were entered into the GUI to let the control system schedule irrigations and automatically turn on/off the valves. The GUI ran the algorithms everyday at midnight and scheduled irrigation events of different plots (if decided) for the following morning at 10:30AM.

Meteorological data of the 2007, 2008 and 2013 growing seasons were obtained from two electronic weather stations in the Washington State Agricultural Weather Network (AgWeatherNet): Roza and WSU HQ weather stations located about 0.5 km and 4.5 km away from the orchard, respectively. In 2007 and 2008, three pairs of IRTs (IRt/c.03™: Type T, Exergen, Watertown, Mass.) with a field view of 17° and an accuracy of ±0.6 °C wired to a Campbell CR21X datalogger (Campbell Scientific, Logan, UT, USA) were used. Two IRT orientations and positions were employed: (a) in 2007 and 2008, the IRTs were pointed at 0° and 45° azimuth and zenith angles, respectively, at both the north and south sides of a tree (Osroosh et al., 2014; Osroosh et al., 2015) and (b) in 2013, three individual IRTs (IRT/c.2) were installed perpendicularly above a tree (~1 m high) at the center of the plots (Sepulcre-Canto et al., 2006; Testi et al., 2008). The IRTs were calibrated/checked using a blackbody calibrator (BB701, Omega Engineering, Inc., Stamford, CT) and shielded by PVC white case. Canopy temperature and meteorological data were acquired every 15 min.

2.4. Manual field measurements

Stem water potential (Ψ_{stem}) was measured at midday (between 13:00 and 15:00) with a pressure bomb (Model 615, PMS Instrument Co., Albany, OR) once per week in the plots under the CWSI-DT treatment from July 31st to October 2nd. Each time shaded leaves from the lower inner part of tree, close to the trunk were targeted. They were enclosed in plastic envelopes covered with aluminum foil, and left attached to the tree for a period of 15–60 min (Fulton et al., 2001). A total of six Ψ_{stem} readings (two readings per tree) were averaged to calculate the Ψ_{stem} corresponding to each sampling date. The Ψ_{stem} measurements were made under different atmospheric conditions including cool, humid and overcast days.

Soil water content was measured using a neutron probe (503DR Hydroprobe, Campbell Pacific Nuclear, Concord, CA) in the center of each irrigation plot where an IRT was mounted. Due to presence of the rocky layer in the study site, soil moisture readings were limited to depths as shallow as 0.6 m in the experimental plots. Hence, measurements taken down to 0.6 m (0.15 m increments) were used for the purpose of irrigation scheduling. PVC access tubes were placed between the drip tubing laterals about 1.25 m from tree trunk. The neutron probe was field-calibrated using soil samples (Evett, 2008):

$$\theta = a\frac{R}{SC} - b \tag{1}$$

where θ is the volumetric soil water content ($\text{m}^3\ \text{m}^{-3}$), R is the neutron probe reading, SC is the standard count, and a and b are the calibration coefficients. To check the accuracy of neutron probe readings, lab calibration was also carried out with soil in barrels annually. The soil water deficit (mm) was calculated as $SWD = D \times [\theta_{FC} - \theta_S]$, where D is the managed soil depth, θ_S is the measured volumetric soil water content. The allowed water deficit (mm) for the managed soil depth was calculated as $AWD = D \times MAD \times [\theta_{FC} - \theta_{PWP}]$.

2.5. Calculation of CWSI

The crop water stress index was calculated after Jackson et al. (1981) and Idso et al. (1981) as:

$$CWSI = \frac{\Delta T_m - \Delta T_l}{\Delta T_u - \Delta T_l} \tag{2}$$

where ΔT_m is the difference between the measured temperatures of canopy (T_c) and air (T_a), ΔT_l is the temperature difference between canopy and air for a well-watered tree canopy (non-limiting soil water availability), and ΔT_u is the temperature difference between canopy and air for a non-transpiring canopy. ΔT_l was computed after Osroosh et al. (2015):

$$\Delta T_l = R_n\frac{1}{\gamma + s} - \frac{1}{P_a(\gamma + s)}VPD \tag{3}$$

where $s = \Delta/P_a$, $VPD = e_s - e_a$ (Idso et al., 1981), e_s is the saturated vapor pressure (kPa) at the air temperature (T_a), $e_a = e_sRH$ is the actual vapor pressure of air (kPa), P_a is the atmospheric pressure (kPa), λ is the latent heat of vaporization (J mol^{-1}), C_P is the heat capacity of air (29.17 $\text{J mol}^{-1}\ \text{C}^{-1}$), Δ is the slope of the relationship between saturation vapor pressure (e_s, kPa) and air temperature (T_a, °C). $\gamma = (g_{Hr}C_P - n)/\lambda g_v$ is similar to the psychrometric constant defined by Campbell and Norman (1998), $g_{Hr} = 2g_H$, and g_H is the air boundary layer conductance to heat calculated as Eq. (4) (Campbell and Norman, 1998):

$$g_H = (1.4)0.135\sqrt{\frac{u}{d}} \tag{4}$$

where u is the wind speed (at 2 m high above the ground) and d is the characteristic dimension defined as 0.72 times the leaf width ($w_l = 5$ cm: measured in the field). The factor 2 accounts for the fact that apple leaves are hypostomatous (Green et al., 2003). R_n and n are defined by the following equations (Osroosh et al., 2015), respectively:

$$R_n = 0.25(\alpha_S S_r + \alpha_S S_t + 4(\alpha_L - 1)L_a) \tag{5}$$

and

$$n = (3\alpha_L - 4)\varepsilon_a(c)\sigma\mathbf{T}_a^3 \tag{6}$$

where $\mathbf{T}_a$ is the air temperature (K), S_r is the global solar irradiance and S_t is the transmitted shortwave radiation through apple leaf ($S_t = \tau S_r$). L_a is the atmosphere longwave flux density computed using the Stefan–Boltzmann equation. τ, α_S and α_L are green leaf transmittance, absorptivity in the short and absorptivity in the thermal waveband, respectively ($\tau = 0.06$, $\alpha_S = 0.85$ and $\alpha_L = 0.95$). α_S was calculated as $\alpha_S = 1 - (\tau + \rho)$ where ρ is the albedo ($\rho = 0.09$). The optical/thermal properties of apple leaf were adapted from Green et al. (2003). g_v is the vapor conductance ($\text{mol m}^{-2}\ \text{s}^{-1}$) estimated using the following equation (Osroosh et al., 2015):

$$g_v = b\frac{P_aR_n}{\lambda VPD} \tag{7}$$

where b is the calibration adjustment coefficient. This equation accounts for the fact apple leaves are well-coupled to the atmosphere and therefore respond to change in relative humidity (Dragoni et al., 2005).

The upper limit, ΔT_u, was calculated by assuming closed stomata for a non-transpiring canopy ($g_v \to 0$), and replacing g_v with zero in Eq. (3):

$$\Delta T_u = \frac{R_n}{g_{Hr}C_P - n} \tag{8}$$

2.6. CWSI-DT irrigation algorithm

To address some of the issues with the conventional CWSI approach, an adaptive CWSI algorithm relying on a dynamic threshold (CWSI-DT) was developed (Fig. 1). The design was based on three major facts: (a) no irrigation is required as long as the index has a decreasing trend, (b) irrigation has to stop if no decrease was observed in the index after several successive irrigation events exceeding soil water holding capacity, and (c) no irrigation is needed if evaporative demand is too low. The

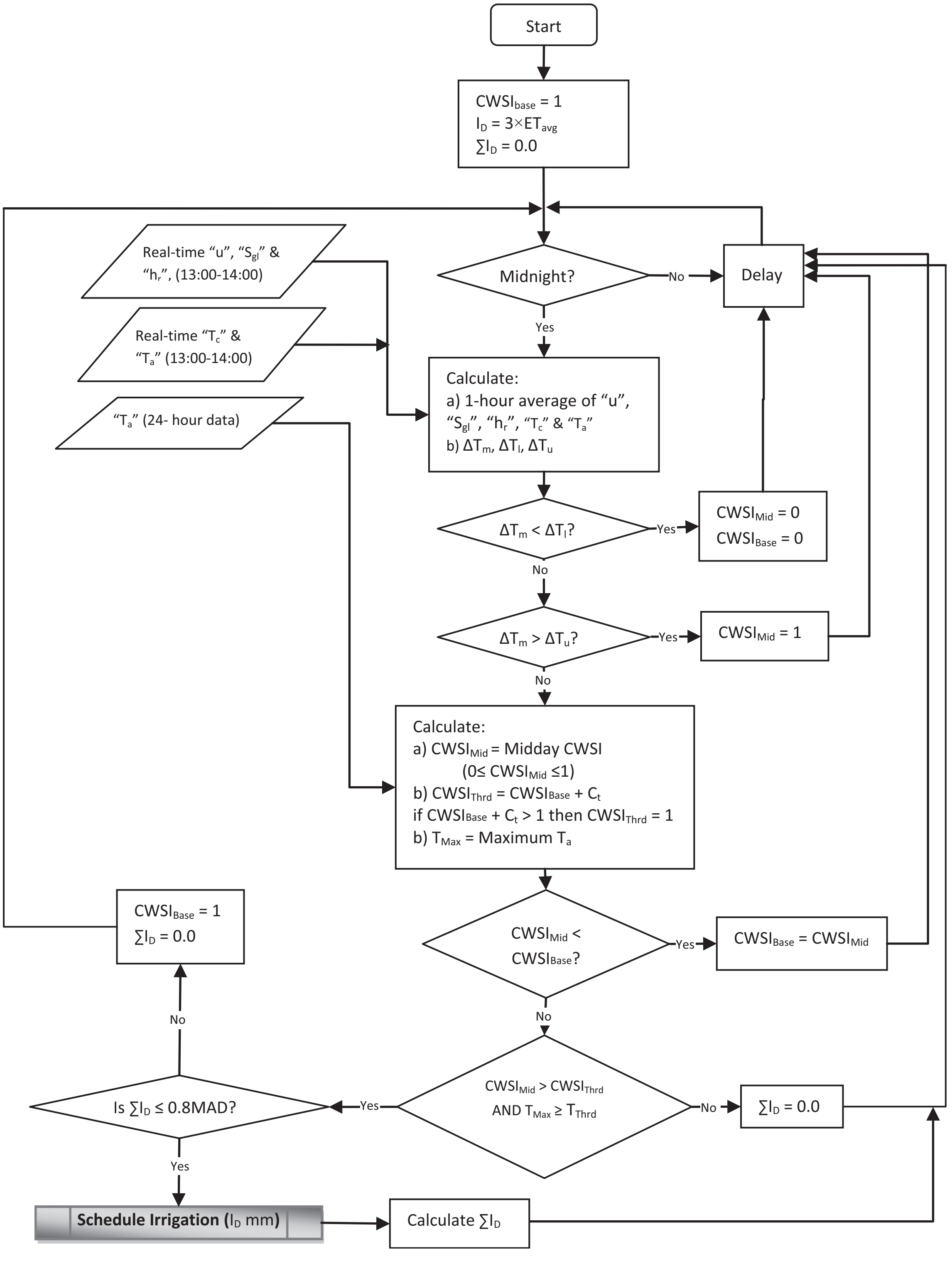

Fig. 1. CWSI-based irrigation scheduling algorithm. 1-h average of thermal and meteorological data (i.e., u, S_{gl}, h_r, T_a, and T_c) collected between 13:00PM and 14:00PM were used to compute $CWSI_{Mid}$. $\sum I_D$ was calculated by adding the water depth of successive irrigations.

CWSI-DT approach and its new terminology are described in the following paragraphs.

2.6.1. Midday CWSI ($CWSI_{Mid}$)

1-h average of thermal and meteorological data (i.e., u, S_{gl}, h_r, T_a, and T_c) collected between 13:00PM and 14:00PM are used to compute midday CWSI ($CWSI_{Mid}$). In the conventional approach, sometimes CWSI is negative ($CWSI < 0$) or is greater than 1 ($CWSI > 1$). The new algorithm limits $CWSI_{Mid}$ to a range between "0" and "1" ($0 \leqslant CWSI_{Mid} \leqslant 1$) by putting the following conditions in place: if $CWSI_{Mid}$ is negative ($\Delta T_m < \Delta T_l$) it is assumed "0" and if greater than "1" ($\Delta T_m > \Delta T_u$) is set to "1".

2.6.2. Base CWSI ($CWSI_{Base}$)

$CWSI_{Base}$ is defined as minimum achievable $CWSI_{Mid}$ by the crop. The algorithm continuously changes $CWSI_{Base}$ in relation to $CWSI_{Mid}$ (if $CWSI_{Mid} < CWSI_{Base}$ then $CWSI_{Base} = CWSI_{Mid}$). The value of $CWSI_{Base}$ depends on many factors including errors caused by uncertainties in canopy temperature measurements, input weather data, and stomatal regulations. In a well-watered tree, $CWSI_{Base}$ might maintain a zero value, be above zero, or constantly change throughout the season.

2.6.3. Dynamic threshold ($CWSI_{Thrd}$)

$CWSI_{Thrd}$ is defined as the sum of $CWSI_{Base}$ and the conventional CWSI threshold, C_t ($CWSI_{Thrd} = CWSI_{Base} + C_t$, If $CWSI_{Base} + C_t > 1$ then $CWSI_{Thrd} = 1$). Like $CWSI_{Mid}$, $CWSI_{Base}$ ranges between "0" and "1" ($0 \leqslant CWSI_{Base} \leqslant 1$). The value of $CWSI_{Base}$ and therefore $CWSI_{Thrd}$ is determined by feedback from the apple trees in response to irrigations.

2.6.4. Algorithm description

To make an irrigation decision four main steps are taken: (a) ΔT_m is compared with both ΔT_l and ΔT_u, (b) $CWSI_{Mid}$ is compared with $CWSI_{Thrd}$, (c) maximum air temperature (T_{Max}) is compared with a temperature threshold (T_{Thrd}), and (d) the total amount of water (net) applied ($\sum I_D$) successively is compared with the water holding capacity of the soil in the MAD fraction. If all of the following conditions are met an irrigation event is scheduled:

(1) $\Delta T_l < \Delta T_m < \Delta T_u$,
(2) $CWSI_{Mid} \geqslant CWSI_{Thrd}$,
(3) $T_{Max} > T_{Thrd}$,
(4) $\sum I_D \leqslant 0.8\text{MAD}$.

If any of the above conditions are not met the following actions will be taken and the program enters a waiting loop:

(1) If $\Delta T_m \leqslant \Delta T_l$ Then $CWSI_{Base} = 0$ and $CWSI_{Mid} = 0$.
(2) If $\Delta T_m \geqslant \Delta T_u$ Then $CWSI_{Mid} = 1$.
(3) If $CWSI_{Mid} < CWSI_{Base}$ Then $CWSI_{Base} = CWSI_{Mid}$.
(4) If $CWSI_{Mid} < CWSI_{Thrd}$ or $T_{Max} > T_{Thrd}$ Then $\sum I_D = 0.0$.
(5) If $\sum I_D > 0.8\text{MAD}$ Then $CWSI_{Base} = 1$ and $\sum I_D = 0.0$.

The algorithm compares T_{Max} with T_{Thrd} and no irrigation is scheduled if $T_{Max} \leqslant T_{Thrd}$. We included this in the algorithm to follow a simple yet useful traditional approach of farmers. They do not irrigate when it is too cold as the ET rate at this temperate is low enough to be neglected. Such temperatures are very probable to be seen early (Day of Year = DOY = 110–143) or late (DOY ⩾ 243) in the growing season. On a very humid, overcast, or cool day, it is very probable that $\Delta T_m > \Delta T_l \approx \Delta T_u$ which results in $CWSI_{Mid} = 1$. This is an uncertain condition and no comparison with the threshold or irrigation management decision is made.

Considering that the control system relies on a feedback from the trees (i.e. canopy temperature) and the irrigation system is high frequency, the quantity of irrigation water is not important (Jones, 2004). Based on this fact, the system applies some amount (discussed later) of water and then waits for the trees to respond. This is to account for a possible lag in the physiological response. If the amount of the water is adequate, it will be reflected in a decreasing $CWSI_{Mid}$. If $CWSI_{Mid}$ is still greater than $CWSI_{Thrd}$, the system keeps watering (on a daily time step) until $CWSI_{Mid}$ drops below the threshold or the total amount of water (net) applied successively exceeds 80% of MAD. At this point $CWSI_{Base}$ is reset to "1". If $CWSI_{Mid}$ drops below the current base, $CWSI_{Base}$ is reset to the lower value. Again, $CWSI_{Mid}$ below zero is assumed "0" and a value greater than "1" is treated as "1".

The required application settings were determined based on the observations in 2007 and 2008. The value of T_{Thrd} was the temperature that farmers in the region traditionally consider too cold to irrigate. The value of C_t, in 2013 was set based on the variations of midday CWSI in well-watered apple trees in 2007 and 2008. The irrigation depth (I_D) was calculated as three times the average crop evapotranspiration (ET_c) in June and July. This amount of water was expected to avoid deep percolation while wetting the root zone at the highest evapotranspiration demand. The daily mean crop evapotranspiration (mmd^{-1}) was computed using the ASCE standardized Penman–Monteith equation (ASCE-EWRI, 2005) in combination with the crop coefficient values adjusted for the local climate (Karimi et al., 2013):

$$ET_c = K_c ET_r \tag{9}$$

where ET_r is the alfalfa reference evapotranspiration (mm d^{-1}).

2.7. Statistical analysis

The statistical measures used were: (a) the mean absolute error (*MAE*), (b) the root mean square error (*RMSE*), (c) a linear regression between midday Ψ_{stem} and *CWSI* in 2013, (d) standard deviation (*STD*) and standard error of mean (*SEM*) as measures of variance, and (e) ANOVA ($p = 0.05$). The *RMSE* was exploited as a measure of the variance between measured ΔT (ΔT_m) and predicted ΔT (ΔT_l) calculated as:

$$RMSE = \sqrt{\frac{\sum(\Delta T_m - \Delta T_l)^2}{n}} \tag{10}$$

where n is the number of measurements. Considering the sensitivity of the *RMSE* to outliers, the mean absolute error (*MAE*) was also used as a safer measure of the variance between ΔT_l and ΔT_m:

$$MAE = \frac{\sum|\Delta T_l - \Delta T_m|}{n} \tag{11}$$

3. Results and discussion

3.1. Midday canopy and air temperature difference

The theoretical non-water-stressed baseline described in Eq. (3) requires one calibration coefficient (b). b-value is used to estimate the vapor conductance, g_v (Eq. (7)). It is a function of fruit load and changes from year to year and as the trees grow older (Osroosh et al., 2014). b-value was determined by minimizing the *MAE* between the simulated ΔT (ΔT_l) and measured values of ΔT (ΔT_m) during mid-season (DOY = 143–243) of 2007, 2008 and 2013 (Table 1). The b-value in 2007 was also used to estimate g_v in other years (second row in 2008 and 2013 in Table 1). Midday values of measured and predicted canopy and air temperature differences (1-h mean) for two years of field investigations are depicted in Fig. 2a–b. Considering the apple trees were

Table 1
Comparison of predicted potential canopy and air temperature difference (ΔT_l) and observed ΔT (ΔT_m). The value of b (first row in each year) was obtained by minimizing the *MAE* between ΔT_l and ΔT_m during mid-season (DOY = 143–243). The b-value in 2007 was also used to estimate g_v in other years (second row in 2008 and 2013).

Year	b	g_v (mol m^{-2} s^{-1})	*MAE* (°C)	*RMSE* (°C)	*STD* (°C)
2007	8.2	0.94	1.0	1.3	0.8
2008	5.0	0.50	0.9	1.1	1.2
	8.2	0.82	2.0	2.2	1.2
2013	2.6	0.41	0.5	0.7	1.7
	8.2	1.30	3.2	3.4	1.7

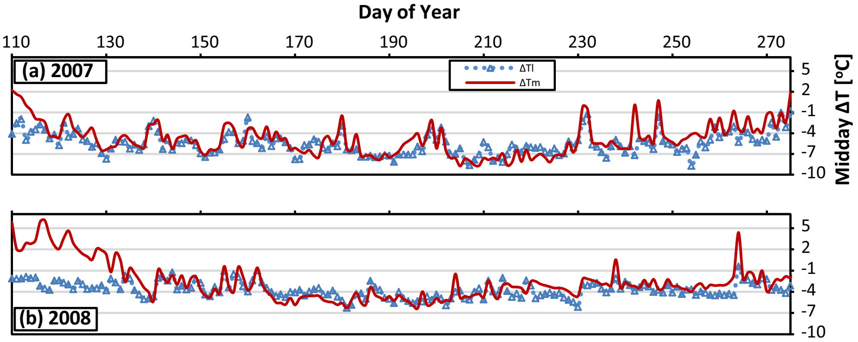

Fig. 2. Comparison of the measured (ΔT_m) and predicted (ΔT_l) canopy and air temperature differences (daily mean) during growing season (DOY = 110–275) in (a) 2007 and 2008 (b).

well-watered, midday ΔT_m was expected to represent the NWSBL for the growing season. The average mid-season g_T values for 2007, 2008, and 2013 were estimated to be 0.94 mol m^{-2} s^{-1}, 0.50 mol m^{-2} s^{-1} and 0.41 mol m^{-2} s^{-1} with corresponding *b*-values of 8.2, 5.0 and 2.6, respectively. The use of *b*-value in 2007 to estimate g_v and ΔT_l in other years resulted in relatively large discrepancy between ΔT_l and ΔT_m. This is one of the reasons why CWSI might not reach a zero value even when the trees are well-watered. The adaptive algorithm, however, was expected to resolve this issue by finding the actual NWSBL by following the trend of CWSI.

The ΔT predictions (ΔT_l) were within a degree of ΔT_m in the experimental years with average *MAEs* of 1.0 °C, 0.9 °C and 0.5 °C in 2007, 2008 and 2013, respectively (Table 1). Moreover, the mean prediction errors in 2008 ($RMSE = 1.1$ °C) and 2013 ($RMSE = 0.7$ °C) were better than that of measurement errors (2008: $STD = 1.2$ °C; 2013: $STD = 1.7$ °C) while in 2007, *RMSE* was about half degree (0.5 °C) higher than the measurement error ($STD = 0.8$ °C). As the ΔT predictions agreed relatively well with the measurements during mid-season when ET_c nearly equals ET_r (Osroosh et al., 2015), it was concluded that the significant difference between early-season ΔT_l and ΔT_m was most probably caused by the error in the measurements of canopy temperature. Due to incomplete canopy growth during early-season thermal readings are affected by the soil background with temperatures much higher than canopies (O'Shaughnessy et al., 2012). This led to erroneous canopy temperature measurements which was more severe in 2008.

ΔT_m, ΔT_l and ΔT_u were calculated ($b = 8.2$) for typical sunny days for non-stressed apple trees at three occasions including early, mid and late in the season in 2007 and 2008 (Fig. 3). As it can be seen, ΔT_m reached its potential value ($\Delta T_m \approx \Delta T_l$) early in the morning during early-season (beyond days when canopy temperature measurements were associated with considerable error) and shifted towards afternoon with potential ΔT_m occurring late in the morning/noon on a mid-season day and afternoon/midday on a late-season day. A similar pattern was detected in many other days during the experimental years. This pattern has also been previously reported in apple trees by Tokei and Dunkel (2005). This could be perhaps considered as another source of error once solar noon/midday is used for detecting water stress especially early in the season. We, however, followed the traditional approach and justified it by the fact that irrigation events were scheduled during mid- and late-season of 2013.

3.2. Soil water status

The use of double laterals for each tree and Silt Loam soil type allowed for a large wetted area of approximately 2–3 m wide (Keller and Bliesner, 1990) with the soil surface layer wet as a result of irrigations. Depending on soil water content, neutron probe can have a sensing volume of up to 4.2 m^3 being large enough to meet required precision for research and irrigation scheduling purposes (Evett et al., 2009). Taking these into account and the fact that access tubes were installed at the center of the wetted area, soil water spatial and temporal variability was not an issue.

The total amount of irrigation water automatically scheduled to the individual plots within the CWSI-DT treatment showed some variability. The total irrigation water scheduled for Plot A ($\sum I_D = 413$ mm; 25 events) was about 32% and 36% more than Plot B ($\sum I_D = 281$ mm; 17 events) and Plot C ($\sum I_D = 264$ mm; 16 events), respectively. Although the amount of applied water to Plot A was larger than the other two plots, soil water content was within the well-watered range in the three plots with no signs of over irrigation. As depicted in Fig. 4a, the mean soil water depletion under the CWSI-DT treatment did not exceed the maximum allowed depletion for apple trees ($AWD = 94$ mm m^{-1}). The variability of applied irrigation water in the plots of the NP treatment ($\sum I_D = 360$ mm, 302 mm and 292 mm) was 37 mm which was slightly less compared to the CWSI-DT treatment ($STD = 82$ mm). There was no significant difference between the means of applied irrigation water in the CWSI-DT and NP treatments ($p = 0.960$). The mean soil water content of the plots under the NP treatment was also close to the well-watered range with occasions of minor under irrigation (Fig. 4b). The means of soil water deficit (during the period of experiment) in the CWSI-DT treatment was significantly lower than the NP treatment ($p < 0.05$). This supports use of the adaptive irrigation algorithm, which responded to the water status of the apple trees as measured by the neutron probe.

3.3. CWSI and Ψ_{stem}

During the growing season of 2013, there were occasional days with overcast sky (Fig. 5). Rainfall from May through September totaled 48 mm, most of which (43 mm) occurred in July. The 2013 season was a relatively warmer year compared to the 2007 and 2008 growing periods. In 2013, the trees maintained relatively high solar noon Ψ_{stem} over the period of the experiment with fluctuations mainly driven by the weather conditions (Fig. 6a). There was no detectable difference between Ψ_{stem} measurements of two sample leaves on an individual tree. Solar noon Ψ_{stem} values were limited to a range with a minimum (mean) of −1.1 MPa and maximum (mean) of −0.35 MPa which was in agreement with the reference values reported in well-watered woody plants in general (De Swaef et al., 2009) and apple trees specifically (Naor and Cohen, 2003). Midday Ψ_{stem} measured in the plots under the CWSI-DT treatment during the period of irrigation (mid to late summer) followed the course of $CWSI_{Mid}$ change very closely (Fig. 6a–b).

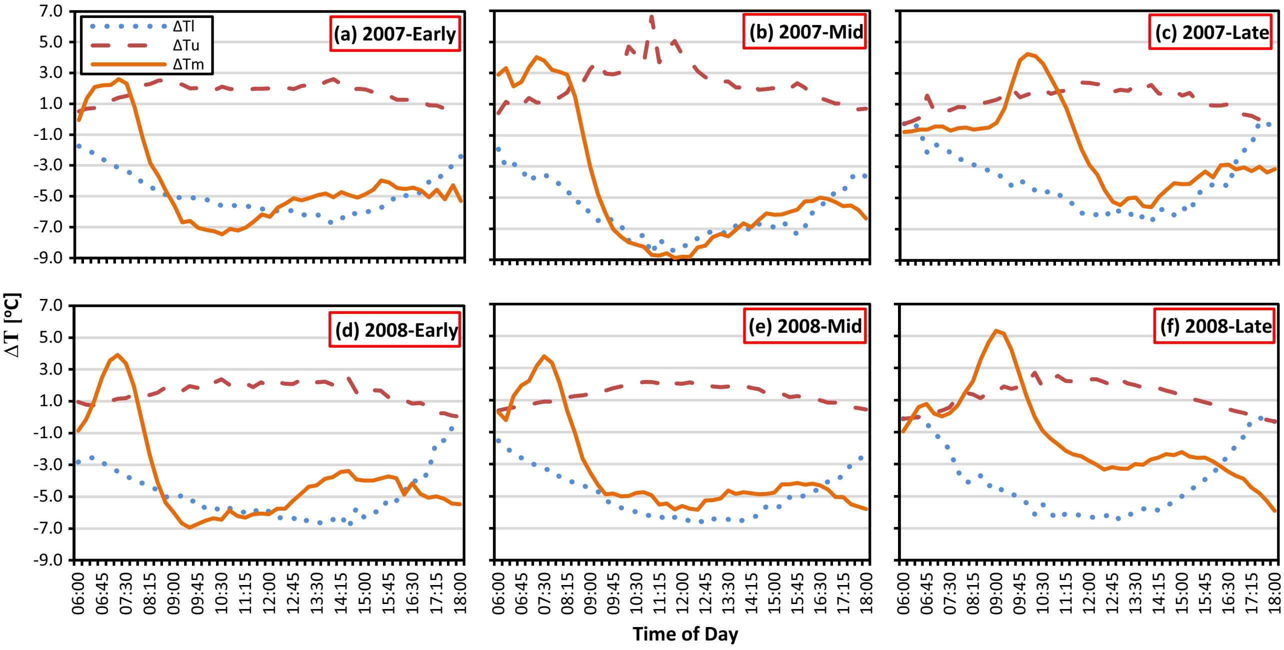

Fig. 3. Diurnal variations of measured canopy and air temperature difference (ΔT_m), ΔT_l and ΔT_u on typical sunny days during early, mid and late in the 2007 (a, b, c) and 2008 (d, e, f) growing seasons.

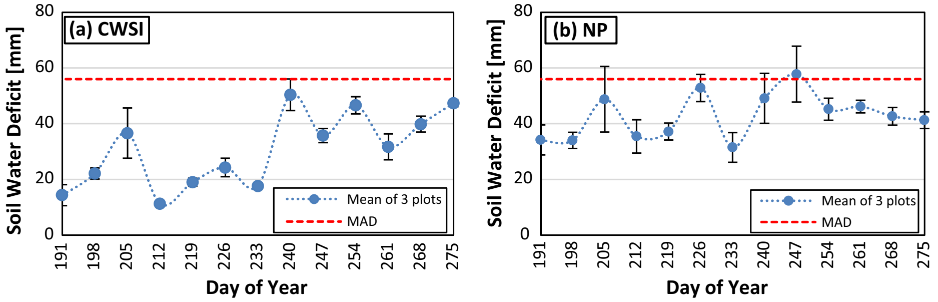

Fig. 4. Soil water deficit of the plots under the CWSI-based algorithm with dynamic threshold (CWSI-DT) (a), and NP (b) treatments measured down to a depth of 0.6 m using neutron probe during the growing season of 2013. The water deficit under the CWSI-DT was below the allowed water deficit (*AWD*) of 56 mm (dotted line) for the measured depth. The error bars show the standard error of the mean.

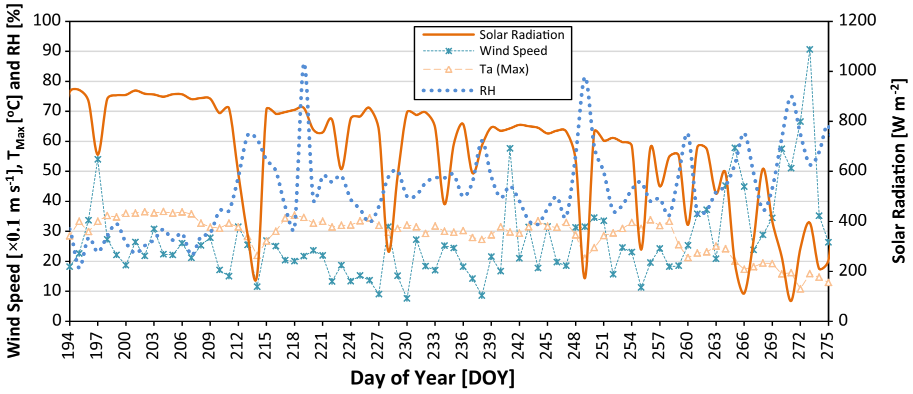

Fig. 5. Midday changes of environmental variables (1-h mean, 13:00–14:00) including solar radiation, relative humidity (*RH*), wind speed, and maximum air temperature ($T_a(Max)$), during the irrigation period of 2013.

As it can be seen in Fig. 6a–b, both Ψ_{stem} and $CWSI_{Mid}$ had a wide range of values under different weather conditions. The highest variability in $CWSI_{Mid}$ was observed on days with low atmospheric demand (i.e. humid, cold and/or overcast) when the signal-to-noise ratio was low (Jones, 2004). In this situation, slight error in the measurement of canopy temperature led to a high *SEM* of up to 0.47. Another reason for the variability was the fact that, although the plots were within the allowed water depletion they were under

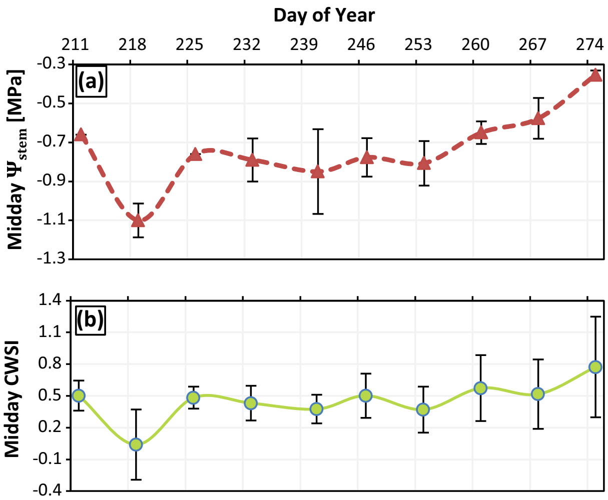

Fig. 6. Seasonal course of midday stem water potential (ψ_{stem}) (a) and midday CWSI ($CWSI_{Mid}$) (b). The error bars show the standard error of the mean. Measurement dates with cloudy, humid and hot weather were as the following: 212 (cloudy), 219 (hot, very humid), 268 (cool, cloudy), 275 (cold, cloudy, moderately humid).

different levels of soil water stress. More stressed trees show a more pronounced change in canopy temperature in response to rapid changes in radiation on cloudy days (Agam et al., 2013b).

To study the relationship between $CWSI_{Mid}$ and Ψ_{stem}, all data from the three plots under the CWSI-DT treatment were pooled together. The linear regression between $CWSI_{Mid}$ and Ψ_{stem}, with an assumption of $b = 8.2$ yielded a significantly strong correlation with $R^2 = 0.91$ ($p < 0.0001$; Fig. 7a). Interestingly, $b = 8.2$ seemed to be an optimum value as other b-values ($b > 8.2$ or $b < 8.2$) resulted in smaller R^2. The agreement between $CWSI_{Mid}$ and Ψ_{stem} was better than the R-squared of the linear relationship between midday ΔT_m and Ψ_{stem} ($R^2 = 0.63$, $p < 0.01$; Fig. 7b).

At first glance, the relationship between $CWSI_{Mid}$ and Ψ_{stem} (Fig. 7a) seems to be inverted as higher/lower Ψ_{stem} values correspond with higher/lower CWSI values. Our results, however, were similar to the observations of Gonzalez-Dugo et al. Gonzalez-Dugoa et al. (2014) for mandarin and orange. This misleading relationship can be explained by the availability of water in the soil and atmospheric demand as discussed by Testi et al. (2008) for pistachio. Considering the trees were maintained well-watered, atmospheric condition played the main role in the variations of Ψ_{stem} (Abrisqueta et al., 2015). Thus, intense transpiration on days with high atmospheric demand (warmer, drier conditions (DOY < 261)) led to lower Ψ_{stem} values whereas under more humid, cooler conditions (DOY $\geqslant$ 261), when the transpiration rate was low, Ψ_{stem} showed to be higher (Fereres and Goldhamer, 2003; Doltra et al., 2007). CWSI is also a function of relative transpiration (Jackson et al., 1981: $CWSI = 1 - \left(\frac{T_a}{T_p}\right)$ where T_a and T_p are the actual and potential transpiration, respectively) which means both transpiration and atmospheric demand determine CWSI value. As discussed, $\Delta T_l \approx \Delta T_u$ on a humid and cool day may result in high CWSI value. Under high atmospheric demand and well-watered condition, on the other hand, CWSI will be closer to 0. This relationship is not valid for trees under deficit irrigation (limiting soil water availability).

3.4. Control algorithm response

Taking $b = 8.2$, $CWSI_{Mid}$ values were calculated using meteorological and thermal data for fully-irrigated apple trees in the growing seasons of 2007 and 2008. Following the farmers in the region, the value of T_{Thrd} was also set for 20 °C. Both the traditional and new algorithms were applied to the generated $CWSI_{Mid}$ data series at the end of the season for evaluation purposes. As in the conventional definition of CWSI threshold, C_t is a site and crop specific value. Here, we took the same approach as in the conventional CWSI threshold to determine C_t. No reference values have been established for most crops including apple trees; however, values close to zero are expected to maintain crops far from being stressed. Higher thresholds are normally used in deficit irrigation (O'Shaughnessy et al., 2012). For the purpose of this study, the control system was set for a conservative value of $C_t = 0.2$ which was similar to the amplitude of midday CWSI variations/fluctuations in mid-season in 2007 ($CWSI_{Mid} = 0.11 \pm 0.12$) and 2008 ($CWSI_{Mid} = 0.26 \pm 0.11$). The net irrigation depth was also set to 16.5 mm ($I_D = 3 \times 5.5$ mm $= 16.5$ mm) to ensure irrigation events replenished the soil water deficit. Considering the low application rate of the drip irrigation system (i.e. 1.1 mm h^{-1}), it took about 15 h to deliver 16.5 mm of water to the trees.

The response of the control algorithm in the plots of the CWSI-DT treatment (i.e. Plots A, B and C) is illustrated in Fig. 8a–c. On some days during the growing season of 2013, $CWSI_{Mid}$ was reset to "1" by the irrigation control algorithm (dotted circles in Fig. 8a). This was in response to high RH and low radiation (DOY = 214, 249) which made it difficult to detect water stress, or low T_a (DOY > 265) which reduced transpiration to a negligible rate. The days on which the measurements of Ψ_{stem} took place included very hot, very cool, overcast and very humid days.

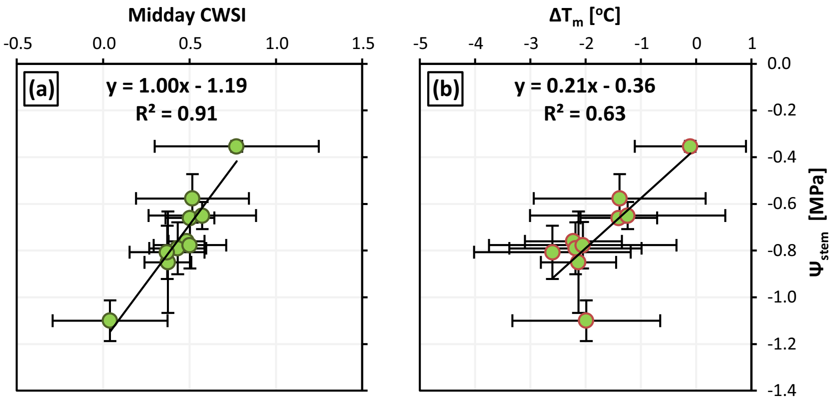

Fig. 7. Linear relationship between midday stem water potential (ψ_{stem}) and midday CWSI ($CWSI_{Mid}$) by assuming $b = 8.2$ (a). Linear relationship between midday ψ_{stem} and midday canopy and air temperature difference, ΔT_m (b). The error bars show the standard error of the mean.

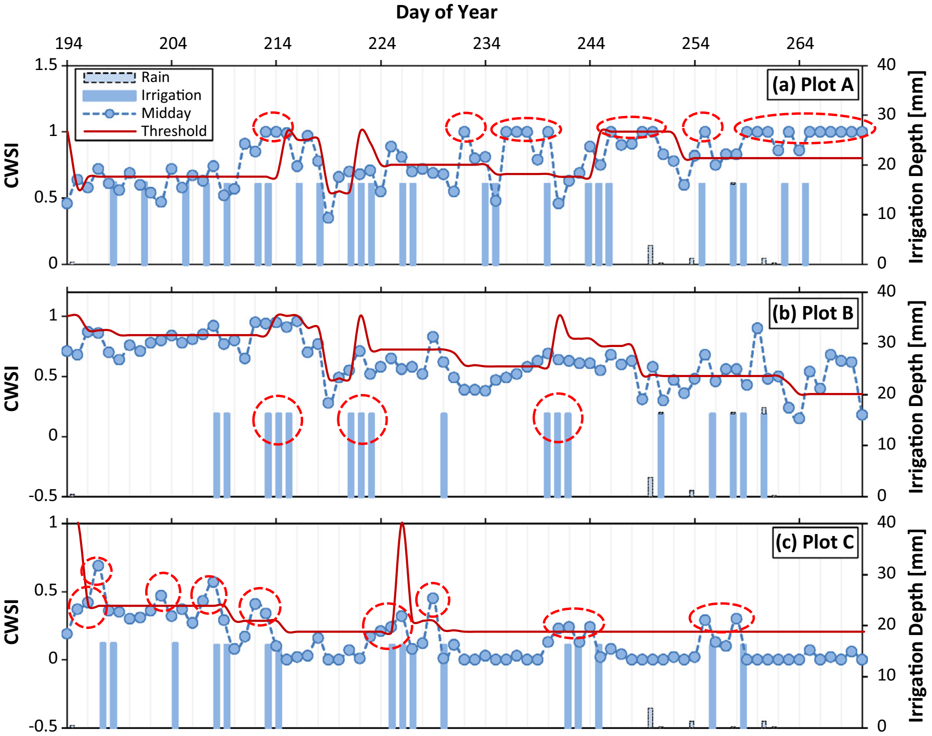

Fig. 8. Application of the irrigation control algorithm to the three plots of the CWSI-DT treatment in 2013: Plot A (a), plot B (b), and plot C (c). The dotted circles in the first figure (a) indicate days on which the irrigation algorithm decided not to irrigate due to low temperature (no water stress) or high relative humidity (not possible to detect water stress). The dotted circles in the second figure (b) indicate days on which the irrigation algorithm stopped irrigating the plot after three successive irrigation events (to avoid excessive watering) and reset the base line ($CWSI_{Base} = 1$). Three irrigation events fulfilled $0.8 \times MAD$, thus after each three irrigations $CWSI_{Mid}$ was reset to "one". The dotted circles in the third figure (c) indicate days on which the irrigation algorithm detected water stress and scheduled irrigation. CWSI dropped to values below the threshold after one or two successive irrigation events.

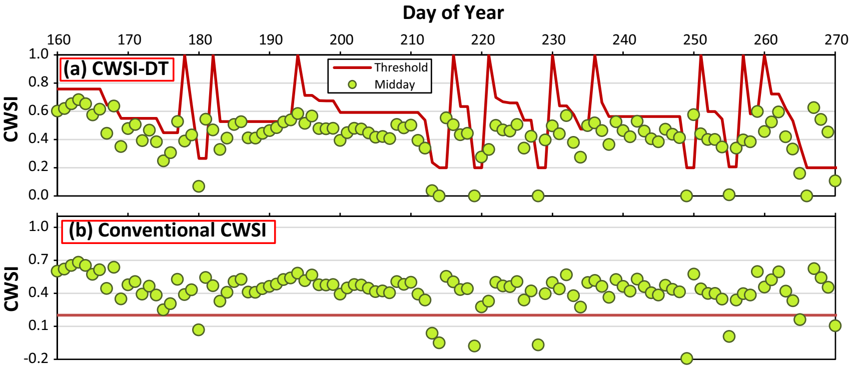

Fig. 9. The new algorithm (CWSI-DT) applied to the meteorological and thermal data of the 2013 growing season (average of three plots) (a). The application of the conventional CWSI approach in 2013 (b).

On a very hot but very humid day (DOY = 219), both Ψ_{stem} and $CWSI_{Mid}$ reached their lowest values at solar noon. On this day, high *RH* and high solar radiation were driving transpiration to opposite directions. The value of $CWSI_{Mid}$ on this day was less than $CWSI_{Thrd}$ in all of the plots. It is known that Ψ_{stem} readings made under unusually cold or overcast days should not be relied on for the purpose of irrigation scheduling (Mitcham and Elkins, 2007; Agam et al., 2013b). Similarly, interpretation of $CWSI_{Mid}$ values calculated on days with low atmospheric demand (i.e. humid, cold, overcast) needs to be carried out with caution. Such a situation occurred on DOY = 275 (Fig. 8b). On a very cool, relatively humid and overcast day like DOY = 275, both midday Ψ_{stem} and $CWSI_{Mid}$ reached their highest values.

On moderately humid, overcast or cool days, on the other hand, $CWSI_{Mid}$ had a value close to "1" (for example $CWSI_{Mid} = 0.99$) and higher than $CWSI_{Thrd}$. This borderline condition was detected as stress by the algorithm. In some cases, this condition continued to persist for several days. The blind act of the control system on these days led to scheduling irrigation events. To avoid excessive watering, however, the control system stopped irrigating a plot after three successive irrigation events (dotted circles in Fig. 8b). This was carried out by resetting $CWSI_{Base}$ to "1" after each three irrigation events which expected to fulfill $0.8 \times MAD$. Regular days on which the algorithm detected water stress and scheduled irrigation are illustrated in Fig. 8c. It can be seen that $CWSI_{Mid}$ dropped to values below the threshold after one or two successive irrigation events.

The thermal readings for plot displayed a relatively large discrepancy. This was not unexpected considering the use of only one IRT per plot and a relatively large non-uniformity observed among the trees in terms of fruit load and shoot growth in 2013.

This resulted in comparatively dissimilar ΔT_m patterns and consequently $CWSI_{Mid}$ in the three plots of the CWSI-DT treatment. Interestingly, the variations of $CWSI_{Mid}$ in 2013 (average of three plots; Fig. 9) were similar to 2007 and 2008, however the mean $CWSI_{Mid}$ was higher ($CWSI_{Mid} = 0.46 \pm 0.11$). A higher mean $CWSI_{Mid}$ in 2013 was mainly due to less fruit load on the trees and consequently a smaller canopy and air temperature difference (Osroosh et al., 2015). The fluctuations of $CWSI_{Mid}$, on the other hand, may be mainly attributed to thermal and microclimatic measurements and partially to the physiology of apple trees as similarly observed in citrus trees (Gonzalez-Dugoa et al., 2014). The results showed that the set threshold constant was large enough to capture natural $CWSI_{Mid}$ fluctuations caused by noise, errors, weather conditions, etc. in non-stressed conditions and lower than a value causing water stress. Overall, compared to the conventional CWSI method, the CWSI-DT irrigation algorithm yielded consistently fewer false irrigation signals on cloudy, humid, or cool/cold days and adapted well to the changing conditions of apple trees.

4. Conclusions

To create the CWSI-DT irrigation algorithm we made a change to the traditional definition of CWSI threshold. The algorithm helped the trees reach their potential transpiration by providing them with enough water and observing their subsequent response. The adaptive nature of the algorithm, through the use of a dynamic non-stressed threshold, allowed for monitoring the water demand of the trees in real-time, avoiding wrong stress signals caused by the effect of the wind, shoot growth or other unwanted factors. It was minimally impacted by CWSI response to temporary atmospheric conditions, IRT installation and measurement errors, apple tree architecture and model uncertainties. The new irrigation algorithm also yielded significantly fewer false irrigation signals on cloudy, humid, or cool/cold days and adapted well to the changing conditions of apple trees. It was concluded that the performance of the irrigation control system was satisfactory.

In the current study, we mainly focused on developing an adaptive algorithm capable of detecting erroneous irrigation signals or limiting water delivery under low atmospheric demands rather than improving CWSI baseline estimations. While it has been developed for and evaluated in apple trees, the proposed adaptive control algorithm is independent of crop or irrigation method because of its logical basis. Application of the new algorithm can also prevent over-irrigation during early-season period when crop canopies are under development, and thus the soil background might interfere with canopy temperature measurements. It is concluded that the crop water stress index can become more efficient in conjunction with a well-developed control algorithm. This is an initial step towards implementing plant-based irrigation scheduling in apple trees. It has the potential to improve water use efficiency, which leads to increased production, reduced production costs, reduced pumping energy requirements, and improved fruit quality.

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