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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