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Comparison of irrigation automation algorithms for drip-irrigated apple trees

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ABSTRACT

Seven irrigation scheduling algorithms and an automatic control system along with a wireless network of soil, thermal and weather sensors were developed and assessed in Prosser, WA in the growing season of 2013. The system was comprised of six wireless sensor and valve actuating nodes installed across an apple orchard, a central base station made up of a transceiver connected to a laptop, and a graphical user interface (GUI). The irrigation algorithms/treatments included the time-temperature threshold (TTT), crop water stress index with dynamic threshold (CWSI), soil-based using granular matrix sensors (SOIL), weather-based using a temperature-only-based evapotranspiration (ET) model and soil water balance (WB), a combination of SOIL and WB (SL + WB), a conventional irrigation practice used in the region (CNTRL), and soil-based using a neutron probe (NP) as benchmark. Different treatments were compared based on the total irrigation water (I_t) applied during the season. They were also compared based on simplicity and expense for a grower to implement. Soil water content (θ_s) and stem water potential (ψ_{stem}) were monitored in a number of treatment plots. The total applied water for CNTRL was significantly higher than all other treatments ($p < 0.001$). The thermal-based TTT and CWSI treatments applied the same amount of water as NP and WB ($p < 0.001$). CWSI and TTT substantially reduced water applied (70%) while maintaining ψ_{stem} within the non-stressed range. In addition, θ_s in the treatment plots of TTT and CWSI did not exceed the maximum allowed deficit recommended for apple trees (MAD of 50%) showing a strong agreement with NP. The SOIL and SL + WB treatments resulted in tangible under-irrigation as leaf drop, decreased leaf turgidity, growth reduction and abnormally small fruits were seen. Among all the strategies, WB seemed to bear the characteristics of being economical, easy to implement and fairly accurate. Our preliminary results also support the use of wireless sensor network for automatic irrigation management of drip-irrigated apple trees.

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1. Introduction

A sound choice of irrigation scheduling method can lead to increased profit and water savings for farmers, reduced environmental impacts and sustainable agriculture (Smith et al., 1996). Proper management of irrigation water to maintain balanced soil water content is crucial for health and productivity of apple trees (Black et al., 2008). To date, research has offered a large number of approaches to detect water stress, compute crop water needs, and automatically schedule irrigation (Al-Kaisi et al., 1997; Orta et al., 2003; Jones, 2004; Farahani et al., 2007; Vellidis et al., 2008; McCready et al., 2009; Ko and Piccinni, 2009; Migliaccio et al., 2010; Romero et al., 2012). Irrigation scheduling approaches may be grouped into three main categories (Zhang and Pierce, 2013): (i) monitoring of soil water status (soil-based), (ii) soil water balance calculations using weather information (weather-based), and (iii) sensing of crop water stress (plant-based).

Automation of irrigation has been evaluated in a number of row plants including tomato, onion and bell pepper using soil sensors measuring tension (Thompson et al., 2007; Enciso et al., 2009) or volumetric water content (Zotarelli et al., 2009). Vellidis et al. (2008) developed and evaluated a real-time, smart soil moisture and temperature sensor array prototype for scheduling irrigation in cotton. Romero et al. (2012) reported that the approach of combining weather data with soil moisture signal could increase irrigation efficiency in almond trees. Tensiometers have been used by Meron et al. (2001) as a feedback to manage irrigation of apple trees. Soil water tension sensors provide a direct measure of plant water status (Pedro Vaza et al., 2013). Watermark™ sensors

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(Irrometer Co., Riverside, CA) have been identified as good indicators of irrigation start and stop (Leib and Matthews, 1999); however, sensor accuracy is contingent to site-specific calibration (Varble and Chávez, 2011). The calibration need of individual sensors can make the use of Watermark™ sensors tedious and unattractive to most farmers, thus very often they are used with only factory calibration. Neutron probe is a scientific-based method for precise measurement of soil water content and has shown to be a reliable reference for other irrigation scheduling techniques (Evett et al., 2009; O'Shaughnessy et al., 2012b).

How change in weather parameters can affect plant water needs can be predicted using an evapotranspiration (ET) model. Frequently used ET models are the Penman-Monteith (PM) (Allen et al., 1998) and Hargreaves (Hargreaves and Samani, 1985) equations. The Hargreaves model requires fewer data than the PM model and can provide estimations of ET using air temperature as sole input (Allen et al., 1998). The most common approach to estimate actual water use of apple trees (ET_c) is to multiply the reference ET (ET_r) by a crop-specific coefficient (K_c) (Lakso, 2003). Osroosh et al. (2014, 2015a) developed models based on infrared thermometry and the energy budget of a single apple leaf to estimate the actual and potential transpiration of whole tree. However, like the PM model, they require a wide range of input data. The weather-based irrigation scheduling has a long history of implementation using commercial irrigation controllers for both research (Davis et al., 2009; Davis and Dukes, 2010; Cardenas-Lailhacar et al., 2008, 2010) and commercial applications; however, few research studies have investigated its application on fruit trees. In a study by Kisekka et al. (2010), ET-based irrigation scheduling saved significant quantities of water compared with a calendar-based grower's approach of irrigation in a Carambola Orchard.

Leaf water potential measured using a pressure bomb has long been used to monitor crop water status and as trigger point for irrigation (Stegman et al., 1976; Turner, 1988). However, this method is very tedious, labor-intensive and not appropriate for automation. The use of infrared temperature of plant canopies along with a number of ancillary meteorological measurements is an alternative plant-based approach (Cohen et al., 2005). Irrigation scheduling systems based on a feedback from crop have shown to outperform scientific-based irrigation scheduling using the neutron probe in row crops (O'Shaughnessy et al., 2015). Various thermal-based scheduling algorithms have been developed such as the crop water stress index (CWSI: Jackson et al., 1981, 1988) and time-temperature threshold (TTT: Wanjura et al., 1992, 1995; Upchurch et al., 1996). CWSI compares the measured canopy-air temperature differences (ΔT_m) with theoretically/empirically determined temperature differences of a non-transpiring (ΔT_u) and well-watered (ΔT_l) plants as defined by Jackson et al. (1981):

$$CWSI = \frac{\Delta T_m - \Delta T_l}{\Delta T_u - \Delta T_l} \quad (1)$$

Different varieties of the CWSI have been suggested over the years including the CWSI and time threshold (CWSI-TT: O'Shaughnessy et al., 2012b), integrated CWSI (iCWSI: O'Shaughnessy et al., 2013) and CWSI-DT (Osroosh et al., 2015b). CWSI has been rarely used to schedule irrigation in trees (Osroosh et al., 2015b) and more often to detect water stress (Testi et al., 2008; Wang and Gartung, 2010; Paltineanu et al., 2013; Agam et al., 2013; Berni et al., 2009; Osroosh et al., 2016). The CWSI might be affected by many unwanted factors such as dust or passing clouds (O'Shaughnessy et al., 2012b); however, it has proven to be reliable if integrated into a robust algorithm accounting for these temporary conditions (Osroosh et al., 2015b).

The TTT method, also patented as "BIOTIC", requires a "time threshold" and a "temperature threshold." The temperature threshold is the optimal leaf temperature for enzyme activity determined in lab. The time threshold is the accumulated time above the temperature threshold for non-stressed crop in specific climate calculated using experimental/simulated data. O'Shaughnessy and Evett (2010) carried out automatic irrigation experiments on cotton using the TTT algorithm in Texas. Peters and Evett (2008) used the TTT method to automate water delivery to the center pivot-irrigated plots of soybean. To our knowledge, no reports are available on irrigation scheduling of woody fruit trees using the TTT approach.

Nowadays, some growers rely on wireless sensor networks (WSN) to obtain information remotely on a wide range of parameters but rarely to automatically schedule irrigations (O'Shaughnessy et al., 2013). In research, WSNs have been employed to collect weather, soil and environmental information using soil moisture, temperature, or agro-meteorological sensors, and to control a variety of irrigation systems (Coates and Delwiche; 2009; Kim and Evans, 2009; O'Shaughnessy et al., 2015; Ojha et al., 2015). A site-specific irrigation control system uses a WSN to monitor field variables and minimize the spatial variability of irrigation. In order to make the wireless technology available to growers, Coates et al. (2013) developed and integrated a valve actuation system with a commercially-available WSN. Both wired and wireless sensors network systems have been used in automatic irrigation scheduling (Peters and Evett, 2008; O'Shaughnessy and Evett, 2010; O'Shaughnessy et al., 2012a, 2013) with the later being more flexible, convenient and economical.

Besides reducing labor requirements, automatic software scheduling tools are necessary for optimizing the amount of irrigation water in response to crop development and type, and environmental conditions (Casadesús et al., 2012). The software must be user-friendly and allow for simple management of the WSN and irrigation valves by growers (Kim and Evans, 2009). Various computer software packages have been developed for monitoring soil parameters and irrigation scheduling over a wide range of irrigation systems (Stone et al., 1985; Hess, 1996; Abreu and Pereira, 2002). Kim and Evans (2009) developed decision support software to collect information from a WSN and control a site-specific linear-move irrigation system on a malting barley field.

The aforementioned approaches have been widely used in research; however, farmers are still far from adopting them. They are eager to see reliable irrigation scheduling methods which are affordable and not necessarily complicated, yet accurate and suit their field and crop conditions. Our specific objectives here were to (i) develop fully automatic irrigation supervisory control and data acquisition (SCADA) system, and wireless sensor network, (ii) develop computer soil-, plant-, and weather-based algorithms for scheduling irrigation of drip-irrigated apple trees, (iii) collect information on these various strategies in terms of total amount of water applied, root zone soil water status (content/tension), plant water status (stem water potential), cost and simplicity. This paper emphasizes on the plant-based approaches and presents the results of a preliminary field evaluation in a growing season in the arid region of central Washington.

2. Materials and methods

2.1. Study area and irrigation system

The study was conducted in a Fuji apple orchard on the Roza Farm of the Washington State University Irrigated Agriculture Research and Extension Center near Prosser, WA (46.26°N,

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