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Author

First Name (or initial)	Middle Name (or initial)	Surname	Role (ASABE member, etc.)	E-mail	Contact author? yes or no
Long		He	ASABE member	luh378@psu.edu	yes

Affiliation

Organization	Address	Country	Phone for contact author
The Pennsylvania State University	290 University Drive, Biglerville, PA 17307	United State	717-677-6116

Author

First Name (or initial)	Middle Name (or initial)	Surname	Role (ASABE member, etc.)	E-mail	Contact author? yes or no
Lihua		Zeng			no

Affiliation

Organization	Address	Country	Phone for contact author
The Pennsylvania State University	290 University Drive, Biglerville, PA 17307	United State	717-677-6116

Author

First Name (or initial)	Middle Name (or initial)	Surname	Role (ASABE member, etc.)	E-mail	Contact author? yes or no
Daeun		Choi			no

Affiliation

Organization	Address	Country	Phone for contact author
The Pennsylvania State University	Shortlidge Road, University Park, PA 16802	United State	

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2950 Niles Road, St. Joseph, MI 49085-9659, USA
269.429.0300 fax 269.429.3852 hq@asabe.org www.asabe.org

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Investigation of Sensor-Based Irrigation Systems for Apple Orchards

Long He[1,2*], Lihua Zeng[1,2], Daeun Choi[1]

[1]Department of Agricultural and Biological Engineering, The Pennsylvania State University, Shortlidge Road, University Park, 16802

[2]Fruit Research and Extension Center, The Pennsylvania State University, 290 University Drive, Biglerville, PA 17307

*Corresponding author: luh378@psu.edu

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Abstract. *Irrigation helps grow agricultural crops in dry areas and during periods of inadequate rainfall. Proper irrigation could improve both crop productivity and produce quality. For high density apple orchards, water relations are even more important. Unit today, most irrigation in tree fruit orchards is applied based on grower experience or simple observations, which may lead to the waste of over-irrigation or the ineffectiveness of under-irrigation. The decision making for irrigation at proper timing for appropriate periods is critical. A series of studies were conducted at a high density apple orchard to investigate the feasibility of irrigation scheduling using sensor information. Four different sensing systems were used to calculate the water status of the crop or soil, including weather data, thermocouple sensor, soil water content sensor, and soil water potential sensor. Then the daily Evapotranspiration (ET), Crop water stress index (CWSI), soil water content threshold, and soil water potential threshold were calculated or identified for scheduling the irrigation. The outcomes from this study provided guideline information to the automated irrigation system with precision scheduling. At last, future improvement and the possibility of implementation were also discussed.*

Keywords. *Precision irrigation, apple orchard, soil moisture sensor, Evapotranspiration, Crop water stress index*

Introduction

In Pennsylvania, fruit and vegetables are grown on over 90,000 acres by about 6,000 farms. Precipitation averages 37 inches each year; thirteen inches of this precipitation runs off directly into streams, while twenty-four inches infiltrates the soil where it may be used by crops (Happer and Lamont, 2017). Uneven precipitation may cause plant stress during critical growth periods affecting both crop productivity and quality. Most horticultural crops in Pennsylvania require supplemental irrigation to minimize plant stress and to increase yield and/or quality. For example, when poor tree growth in a newly planted orchard results from inadequate water availability, maximum cropping may be delayed for years, peak investment is increased by 20%, and total profits are reduced by 66% over the 20-year life of the orchard (Robinson et al., 2013).

Compared to advances in other areas of agricultural technology, such as GIS-guided harvesting or aerial crop monitoring, development of irrigation and water management technologies has lagged. As sensing technologies develop and become more affordable, and the "Internet of Things" (internet connectivity among everyday items) becomes more prevalent in society, better water management practices through precision and automated irrigation systems become possible. Three problems associated with every irrigation system are timing (when to initiate and when to cease water application), the application rate (volume per unit time), and location (where water is applied). Micro-irrigation (the control of irrigation on a per-plant basis) provides a solution to the latter problem and somewhat addresses the problem of application rate. Micro-irrigation technology in the form of trickle irrigation has been in use since the 1950's (Boyce, 1960). Precision irrigation as defined in a modern irrigation management context controls plant water stress at critical growth stages by applying only the necessary amount of water directly to the crop, varying rate and duration as needed (Casadesus, 2012; O'Shaughnessy and Evett, 2010; Dorsey, 2017).

Adoption of precision irrigation systems for use in modern fruit production systems will require the development of integrated sensing, control, and decision-making technologies to adequately control timing, rate, and distribution of water when needed (Smith and Baillie, 2009). Different sensor systems and technologies have been investigated and tested for precision irrigation, including weather-based (Dragoni et al., 2005), soil-based (Osroosh et al., 2016) and plant-based sensor systems (Conaty et al., 2011), and the advanced control and communication systems necessary to put in communication multiple components of an irrigation system (pumps, solenoids, etc.). Every irrigation and sensing technology have strengths that recommend it for certain applications but also has disadvantages that limit its effectiveness in other situations.

To investigate an efficient irrigation strategy for apple orchard in the mid-Atlantic region, different sensing systems were studied, and the irrigation events were scheduled based on the calculation/recorded data. The objectives of this study include: 1) monitoring the soil/crop water status with different sensing systems; 2) investigating the feasibility of variable irrigation scheduling strategies with sensing systems.

Materials and Methods

Test Field and Experimental Setup

To achieve the proposed objectives, a series of sensor-based irrigation tests were conducted in a research orchard at Penn State Fruit Research and Extension Center (Biglerville, PA). The orchard is a 0.9-acre Fuji block, locating at a relative high elevation. There are total nine rows of apple trees. A drip irrigation system was installed in the test block. The emitters were spaced at 60 cm along the pipeline, the size of the pipe is 13 mm. Figure 1 shows the layout of the experimental design. Four irrigation treatments were designed, and two rows of trees were used for each treatment. The treatments include conventional method which is determined by the experience of the operator; ET based irrigation, which was based on the calculation of the daily based ET and rainfall; crop water stress based irrigation, and soil moisture sensor based irrigation. The experiment started at early June until the harvest of the crop on the middle of October.

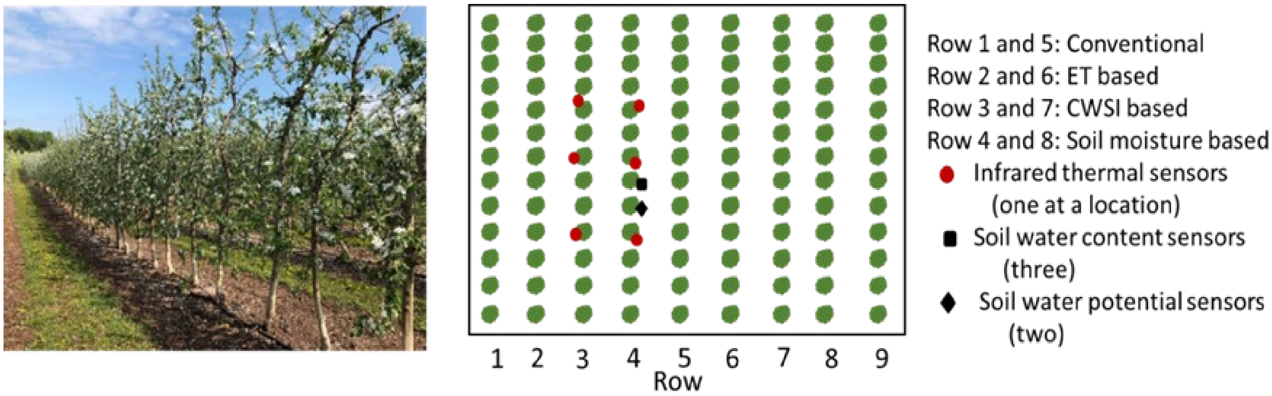

Figure 1. The experiment site of a high-density Fuji apple block (Left) and the experimental setup for sensor-based irrigation test (Right)

Sensor System Setup

Soil Moisture Sensors

The goal of a well-managed irrigation program is to maintain soil moisture between field capacity and the point of allowable depletion, or in other words, to make sure that there is always readily available water. Although apple roots can grow to a depth of several yards, nearly all of the roots of mature tree are typically in the top 30 to 36 inches (Atkinson, 1980). Two types of soil moisture sensors, namely, water content sensor (TEROS 12, Meter Group, Pullman, WA) and water potential sensor (TEROS 21, Meter Group, Pullman, WA), were used in the study. Figure 2 shows the installation and the data acquisition for these sensors. In this study, three soil water content sensors were installed at different depths under ground, e.g. 30, 60, and 90 cm under the ground. Two soil water potential sensors were installed at the depth of 45 and 75 cm. A data logger (EM60, Meter Group, Pullman, WA) was used to record all the sensor data at 10 minutes rate.

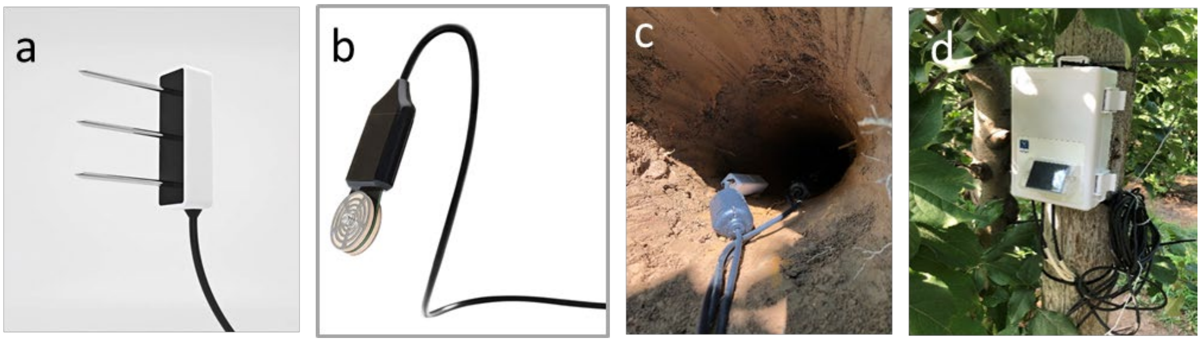

Figure 2. Soil moisture sensor systems. a) soil water content sensor; b) soil water potential sensor; c) installation of sensors; and d) sensor data acquisition

Weather Information

Weather-based irrigation is also referred to evapotranspiration (ET)-based irrigation. ET-based irrigation requires a complete set of weather parameters from a nearby weather station to calculate ET rate. In this study, these weather data were acquired from a nearby weather station in a network system called NEWA (the Network for Environment and Weather Applications), including solar radiation, wind speed and direction, precipitation, relative humidity (RH), and air temperature. The information was used for the calculation of the daily ET and the water deficit for the test orchard.

Infrared Thermal Sensor

Canopy temperature has been shown to be an indicator of plant water stress (Jackson et al., 1981). Infrared thermal sensor is a good way to measure the canopy temperature to assess crop water stress. A set of infrared thermocouple sensors (IRt/c.3x, Exergen Corporation, Watertown, MA) were used in our study to measure the canopy temperature. Figure 3 shows the thermal sensor, data logger (CR6, Campbell Scientific, Logan, UT), the installation of sensors in the field, and the data acquisition system. The sensors were mounted on the top of the canopy within about 30 cm distance with facing down to the tree leaves. Six sensors were installed in two neighboring rows, and the data was recorded at 5 minutes interval into the data logger.

Figure 3. Infrared thermal sensor system setup, a) Infrared thermal sensor and datalogger; b) the installation of the thermal sensor on the top of tree canopy; c) data acquisition system

Measurements for Irrigation Scheduling

Soil Water Content and Soil Water Potential

The state of water in soil is described in terms of the amount of water and the energy associated with the forces which hold the water in the soil. The amount of water can be defined as soil water content, and the energy state of the water is soil water potential. In this study, the water content sensor and water potential sensor were installed at the same row to compare the two type of information. The field capacity varies for diffferent types of soil, could range from 10% to 35% (Black et al., 2008), the 30% of water content was estimated for starting the irrigation in this study. With the selected water potential sensor and the estimated soil type, the value of -10 kPa was set to threshold for wet soil, and -80 kPa was set to the threshold for dry soil. The thresholds for dry and wet soil can be used for the start and stop irrigation event.

Daily ET

The daily reference ET (ETr) was calculated using the Hargreaves model (Hargreaves and Samani, 1985), which was described in detail in FAO-56 Hargreaves equation (Allen et al., 1998). The model must be modified to suit different growing conditions and the disparate plant architectures of tall discontinuous crops like fruit trees. Then the reference ET was adjusted by local crop coefficients Kc. While, the Kc could be slightly different at different crop growing stage. In this study, we used a constant value of Kc=0.9 for apple tree orchard through the season. For simplification, the effective rainfall was assumed to be equal to the amount of rainfall from the nearby weather station. The daily water deficit was defined as the input water (rainfall) subtracting the daily evapotranspiration, as shown in equation 1.

$$W_d = ET_C - R_e \qquad (1)$$

Wd is the daily required irrigation water, and the Re is the rainfall of the day.

The water deficit was calculated daily, and it was accumulated through the time. When the water deficit reaches certain value setting to 25.4 mm (1 inch), then the irrigation will need to be scheduled. Our irrigation goal was to reduce the water deficit to zero. In our calculation, if the rainfall/irrigation was greater than the current accumulated water deficit, the value of accumulated water deficit was set to zero at the end of the day (the extra water was regarded as run-off). The water deficit was set to zero at the beginning of the season, with soil water content at field capacity was added to soil prior to the test.

Crop Water Stress Index (CWSI)

Crop water stress index (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 show signs of stress. The CWSI based approach of irrigation scheduling used a static/fixed threshold to trigger the irrigation signal. The CWSI value for a crop under no stress is normally assumed to be zero, and for a severely stressed crop to be close to one. The CWSI can be calculated using the equation below.

$$CWSI = \frac{\Delta T_m - \Delta T_l}{\Delta T_u - \Delta T_l} \qquad (2)$$

Where ΔT_m is the difference between the measured temperatures of canopy (Tc) and air (Ta), ΔT_l is the temperature difference between canopy and air for a well-watered tree canopy, and ΔT_u is the temperature difference between canopy and air for a non-transpiring canopy. The theoretical lower and upper boundaries of the CWSI were calculated using biophysical models thoroughly detailed by Osroosh et al. (2015).

Results and Analysis

ET Based Water Deficit and Irrigation

As shown in Figure 4, the daily ET, accumulated deficit based on the calculated daily ET, irrigation and rainfall are presented from early June to the middle of October. Three irrigation events were applied in this treatment. The first irrigation was applied even the accumulated water deficit was not reach to the threshold, and the irrigated water was more than the deficit. The water deficit was set to zero at the end of the day. Between day 184 and 192, there was very little rain, and the daily ET was high for most of the days. The accumulated deficit was over the setting value of 25.4 mm at day 192. Then the second irrigation was applied. For the second irrigation event, 12.7 mm of water was applied in the first day and another 25.4 mm of water was applied in the next day. It recorded a 32 mm rainfall on the day 198, while the test block seems did not get that much due to the location of weather station is at certain distance to the test block (we can also see the water content changes in the next subsection). The irrigation event was applied then even the water deficit was very small. The irrigated water was 12.7 mm for this time, which is the third irrigation event for this treatment. On the day of

250, the accumulated water deficit exceeded the threshold, while heavy rain was forecasted in the following days. After that, there was no irrigation event applied, because the estimated deficit was under the irrigation threshold attributing to the small daily ET and sufficient rainfall.

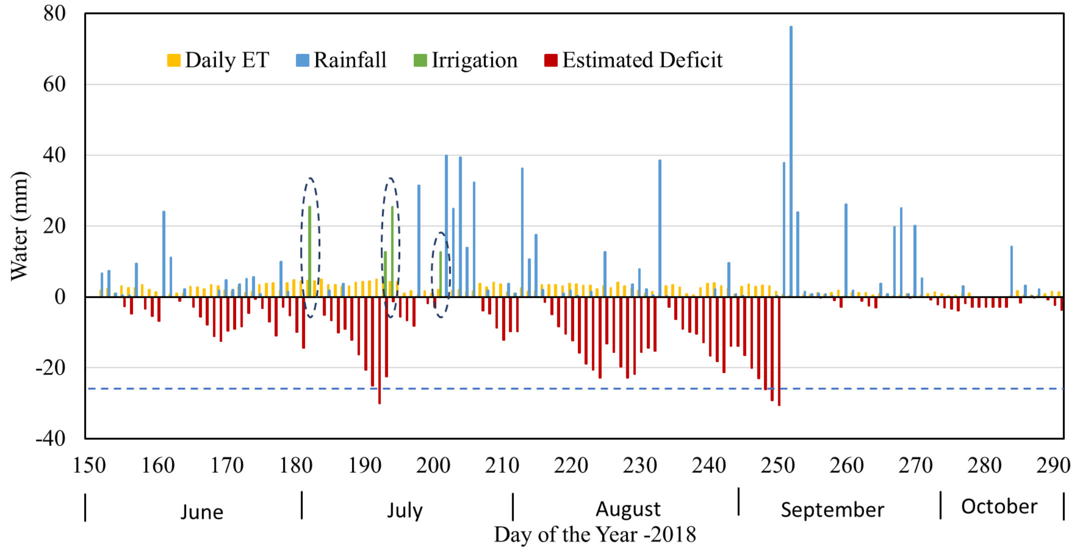

Figure 4. Daily ET, rainfall, irrigation, rainfall and the daily water deficit of the tested orchard

Water Content and Irrigation

Figure 5 shows the daily average soil water content through days. In the Figure, WC #1 to WC #3 represent three water content sensors from top to bottom in the ground. The daily averaged water content, rainfall, and irrigation water are illustrated. As shown in figure, the reading of the top two sensors were similar, while the very bottom one reached up much high soil water content when the irrigation was applied, or the rainfall occurred. While the three numbers were getting close after a few days of these events. As the soil getting deeper, more clay is in the soil, which may cause the higher water content at the bottom of the tree root, and another reason is that the water goes down from top to the bottom of the ground, and the over irrigated water or rain water may need more time to run off. A water content threshold of 0.30 m^3/m^3 was set for the irrigation. The water content values from three sensors increased after a few hours of irrigation and reached the field capacity at the end of the irrigation event. Take the first irrigation event for an example, the soil water content from the top two sensors reached about 0.35 m^3/m^3 on daily average. While, that of the bottom could reach up to more than 0.4 m^3/m^3. Figure 6 shows the soil water content changes on hourly basis from the three sensors.

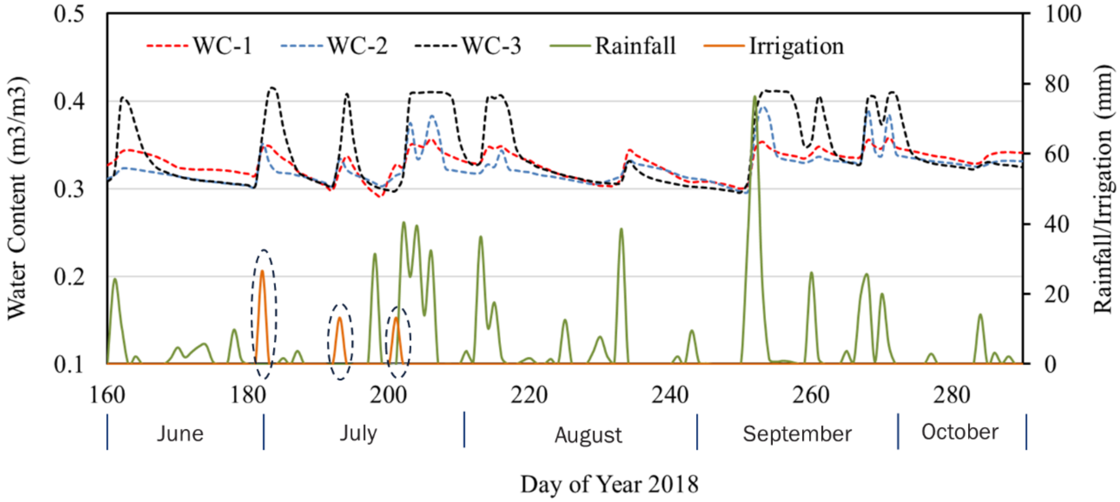

Figure 5. Soil water content through days from early June to middle October

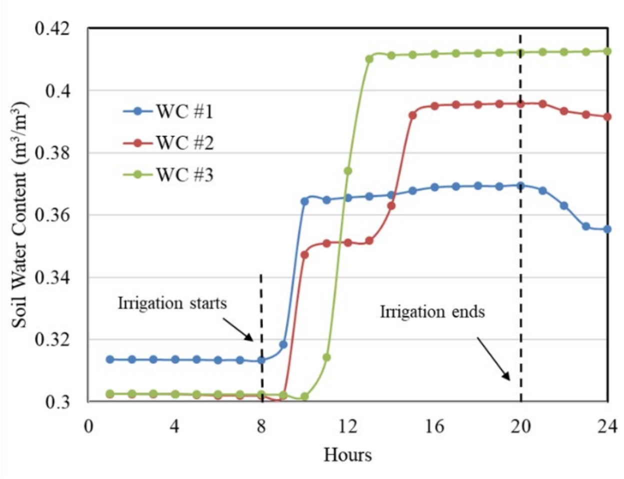

Figure 6. Soil water content changing during an irrigation event at hourly interval

As shown in Figure 6, the irrigation event started at 8:00 am, and ended at 20:00 pm, with total of 12 hours of irrigation. About 25.4 mm water was applied to the soil for apple trees. The soil water content at the top portion of the root zoom increased firstly after the irrigation event started, and then deeper ones followed. After a few hours of irrigation, the soil water contents at different levels were maintained at a consistent level, especially after 15:00 pm. At the very last few hours of irrigation, the water content in the soil was not increasing, which could be considered the maximum water holding capacity for the soil at these depths. Therefore, it would be reasonable to stop the irrigation at earlier time to save some water. More studies/cases will be conducted to identify an effective irrigation ending time when the soil water content sensors are using for the irrigation scheduling in apple orchards.

Water Potential and Irrigation

Figure 7 shows the daily average soil water potential through days from June to October 2018. In the Figure, WP #1, and WP #2 represent two water potential sensors from top to bottom in the soil. The daily based water potential, rainfall, and irrigation are illustrated. As shown in figure, the reading of the two sensors were similar. Throughout the season, almost half of the time the values of two sensors were about -10 kPa due to too much of rainfall. When the soil started to get dry, the top sensor reached up slightly lower value (with higher minus value), which means drier at the top portion of the root zone. A threshold was set for the irrigation, in this study, -80 kPa was used for the threshold (different soil type has different threshold). After the irrigation event, there is an obvious change of the soil water potential, which went close to -10 kPa. The water content reached the field capacity at the end of the irrigation event. Figure 8 shows the soil water content changes on hourly basis from the two sensors.

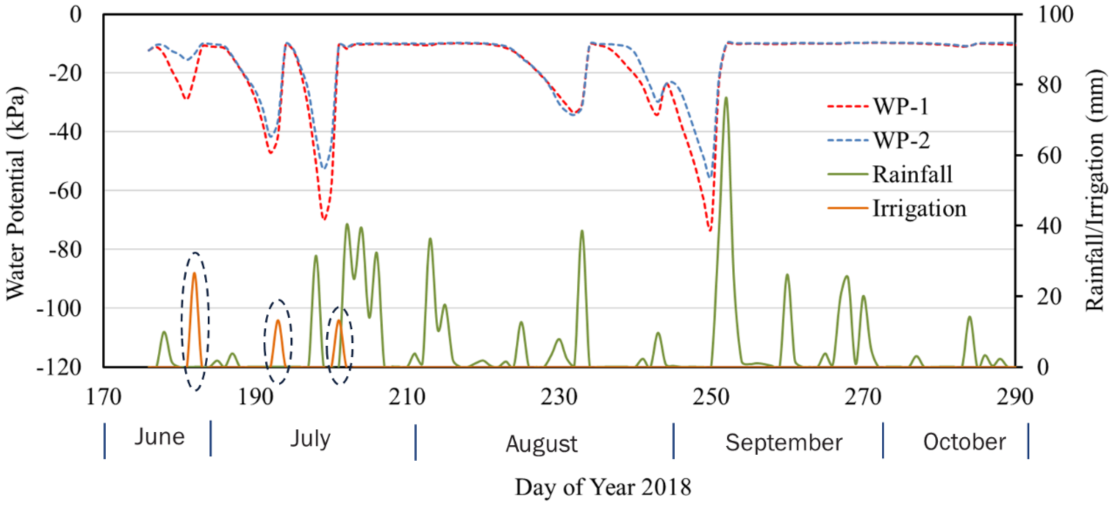

Figure 7. Soil water content through days from early June to middle October

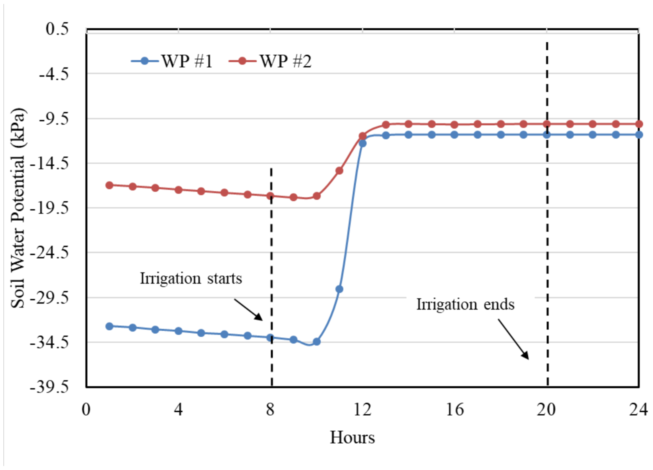

Figure 8. Soil water potential changing during an irrigation event at hourly interval

The same as Figure 6, the irrigation event started at 8:00 am, and ended at 20:00 pm, with total of 12 hours of irrigation. About 25.4 mm water was applied to the ground for apple trees. Both readings continued to decrease at the first two hours after the irrigation, while dramatically increased to the value around -10 kPa. After 13:00 pm, the soil water potential at both locations kept the consistent at this maximum value. Therefore, it would be possible to save some water if the irrigation event ended after 13:00 pm or couple of hours late to make sure the water could go to the whole root zone. The result was compatible to the soil water potential changes in the soil as shown in Figure 6, which also indicated that after 13:00 pm, the values were only changed slightly. More studies/cases will be conducted to identify an effective irrigation ending time when the soil water potential sensors are using for the irrigation scheduling in apple orchards.

CWSI and Irrigation

The crop water stress index (CWSI) was calculated throughout the season for the test tree row using the canopy temperature (Tc) and weather data, such as air temperature (Ta), relative humidity (RH), day of the year, wind speed, and solar radiation (Figure 9). The CWSI is a value between 0 and 1, with larger number indicating more on water stress. A threshold value of CWSI was selected for the decision of irrigation event, based on the previous studies, 0.4 was selected in our study. CWSI was calculated on daily base to indicate the stress status of the crops directly. From the results, we can find that in most of days, the CWSI values were less than 0.4, while there were a few of them close to 1. Look into these days with large CWSI, either it was a very humid day with relative humidity greater than 85%, or the average air temperature was below 65 F. Typically, if the plant is water stressed, then it will close the stomata and restrict water loss and therefore the plant leaves will be relatively warmer than a non-stressed plant. While, when the weather is too humid (RH is large) or the air is too cool, then the difference of the temperature between leaves and atmosphere is small, which could result in large CWSI but the crop may not be necessary under stress. Therefore, the current model for calculating the CWSI is more feasible for clear days with high temperature.

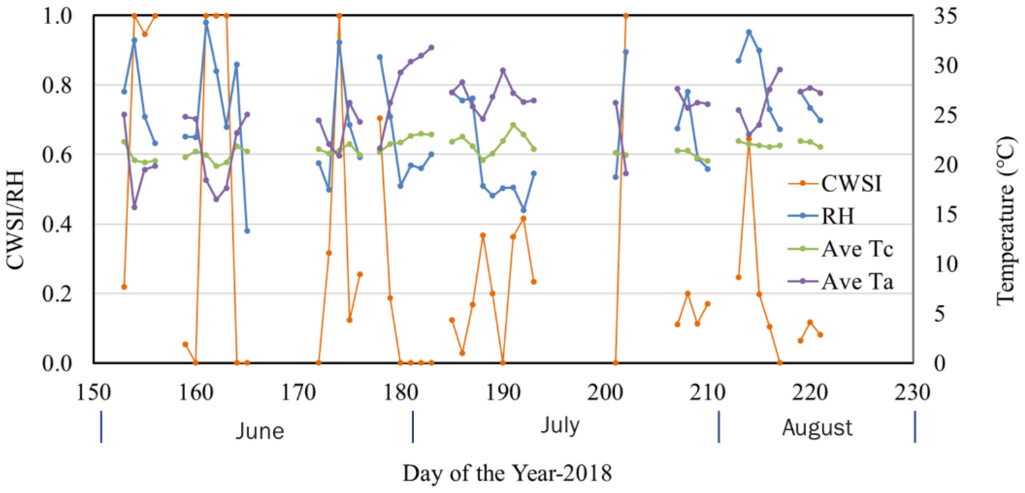

Figure 9. Crop water stress index and other specifications of the monitored tree rows

The year of 2018 is a wet year, we had much more rainfall during the growing season comparing to regular years, resulting in no much need for the irrigation. While the sensors we tested in the season, as well as the data we connected and analyzed provided very useful information for the irrigation scheduling and will be very helpful for our future studies. The two types of soil water moisture sensors indicated the water status in the soil for apple trees with easy accessibility, while they are not presenting the tree canopy stress directly. The CWSI measured the water stress of the canopy directly, while it has certain challenge to be measured accurately. In the future, the combination information of water status and canopy water stress could be considered to provide more efficient irrigation scheduling. Meanwhile, the soil water hold capacity will be investigated more to provide more precise irrigation scheduling, with considering using both water content and water potential sensors at the same time. At last, the weather information and its effects on the crop water need, and the water need for different stage of crop growth would be something else to be considered in the future.

Conclusion

This study investigated a few sensor-based irrigation strategies for precision irrigation of apple orchards, including ET-based, soil moisture based, and CWSI based strategies. A series of field test were conducted in a high density apple orchard. The following specific conclusions can be drawn from this work.

1. The soil/crop water status was indicated with the test sensor systems, and irrigation was applied based on the calculated or recorded parameters with the defined thresholds. With the information acquired from the 2018 season, the more precision method will be used for large scale application.

2. By comparing those four sensing systems, the water moisture based method was relatively easy to apply with directly identified thresholds, while the ET based and CWSI based method needed information from nearby weather station and required some experienced formulas to calculate. The ET based irrigation may cause certain error due to the accumulated water deficit method used in this study. The CWSI method had limitations on the weather condition (high humidity), and the algorithm needs to be modified in the future to consider the variation of the weather conditions.

In overall, the tested sensor-based systems provided the guideline information for precision irrigation in apple orchard. In the future, more precision irrigation strategies will be investigated by considering the combination of two or more sensor systems, and the sensor decision making system will be used for automated irrigation system for the tree fruit orchards.

Acknowledgements

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