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Proximal Sensing of Leaf Temperature and Microclimatic Variables to Implement Precision Irrigation in Almond and Grape Crops

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Abstract. *Irrigation decisions based on traditional soil moisture sensing often leads to uncertainty regarding the true amount of water available to the plant. Plant based sensing of water stress decreases this uncertainty. In specialty crops grown in California's Central Valley, precision deficit irrigation based on plant water stress could be used to decrease water use and increase water use efficiency by supplying the necessary quantity of water only when it is needed by the plant. However, there is a lack of a clear decision support system to implement stress-based precision irrigation on a management unit basis. Management zones were developed using an unsupervised fuzzy classification technique, where zone divisions were based on the soil characteristics of digital elevation, shallow electrical conductivity, sand, silt content and plant characteristics (leaf temperature and canopy cover). Management zones were most influenced by digital elevation. In both almonds and grapes, two zones were identified and two treatments were implemented. A leaf monitor was used to proximally sense the leaf temperature and microclimatic variables (relative humidity, air temperature, wind speed, and incident radiation) and compute a crop water stress index in almond and grape crops. Temperature differences between leaf surface and air were used to obtain stress indices. A wireless mesh network system was used to interface 14 leaf monitors in the almond plot* *while 10 leaf monitors interfaced to hubs equipped with cellular modems were used in the grape plot. In both cases data were transmitted to the web where they could be accessed in real-time to guide irrigation decisions. Plant water stress was estimated with respect to a well-watered and a simulated dry control tree. Variable rate irrigation was applied in almonds according to crop water stress levels in each management zone. Plant stress was evaluated in grapes in eight groups of five vines over a period of 10 days, where four groups were recovering through irrigation after experiencing severe stress and the other four groups were stressed by not applying water to the vines. In grapes, MCWSI and DSWP were found to be linearly related with a coefficient of determination value of 0.82. In almonds, a strong correlation resulted from comparison of CWSI and DSWP, obtained for each treatment of each zone; this yielded a second order polynomial relationship with a coefficient of multiple determination value of 0.79. In almonds, preliminary results indicated that Zone 1 required only 70% water compared to the grower treatment while Zone 2 required about 90% water compared to the grower treatment. These results suggest this method has the potential for increased water savings and increased water use efficiency.*

Keywords. *Deficit irrigation, leaf monitor, wireless network, precision irrigation, crop water stress index, management zones*

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Introduction

Irrigation withdrawals in the United States account for over 60 percent of the country's total freshwater withdrawals, excluding thermoelectric power uses (Maupin et al. 2010). Agricultural production in the Western U.S. requires irrigation to supply crops with the water needed to grow during dry summers. Because of its unique climate, California grows a large number of specialty crops which require irrigation. This amounted to 65% of water used by California being used for agricultural irrigation in 2010 (Maupin et al. 2010). At current usage levels, California withdraws more freshwater than any other state (Maupin et al. 2010). Lack of water resources combined with climate change predictions highlight the need to develop methods which increase water use efficiency through improved management of crop irrigation systems (Anderson et al. 2008).

Modern irrigation management is still largely dominated by evapotranspiration estimates and soil moisture measurements. However, it is difficult to accurately represent root zone soil moisture, given the distribution of roots throughout the root zone (Jones 2004; Naor 2008). Additionally, there is some argument that actual soil moisture content may decrease significantly before a reduction is seen in the water available for plant use and it is difficult to define a threshold of stress based on soil water content (Lampinen et al. 1999; Naor 2008). McCutchan and Shackel (1992), and Levitt (1980) asserted that methods based on soil water balance techniques did not directly relate to plant water stresses, as plants can often develop mechanisms to tolerate stress. Still, soil water status sensors remain one of the more popular methods for irrigation scheduling likely due to the straightforward interpretation of their results and their ability to provide continuous data via the web (Phene et al. 1990; Howell 1996).

The need for plant-sensed data arises from the fact that functioning of a plant's physiology depends on both the soil water potential, or the bulk amount of water available in the soil, as well as its tissue water potential (Jones 2004). This results in changes in the plant hydraulic flow resistance, seen as variability in plant water stress. Plant-based methods can suggest irrigation timing by sensing a physiological response to water stress. The successful implementation of plant based techniques depend on the type of crop grown and the parameters the grower deems most relevant (Naor 2008). Plant-sensed irrigation decisions provide growers with the ability to water only when needed by the plant. Measurements based on plant water status (PWS) provide the critical information required to implement efficient irrigation management systems in orchards and vineyards.

Traditional measurements of plant water stress levels require tedious and time-consuming sampling using a pressure chamber, which requires personnel to make specialized measurements in the field. Historically, this has hindered their use as a guide for irrigation management decisions. To address this, a mobile sensor suite was developed which predicted PWS via measurement of leaf temperature and microclimatic variables (Dhillon et al. 2014a). In that study, leaf temperature correlated well with PWS and microclimatic variables- specifically stem water potential (SWP), air temperature, relative humidity, and incident radiation- for shaded leaves, with coefficient of multiple determination (R^2) values of 0.90, 0.86, 0.86 for almond, walnut and grape crops, respectively (Dhillon et al. 2014b).

At a conceptual level, the benefits of plant sensing based irrigation are fully realized when variable rate deficit irrigation is achieved. Some studies show that maintaining a moderate level of plant stress can decrease water use and increase water use efficiency without affecting yield, after full canopy is established. In fact, some research has indicated that a 10 to 15% reduction in water use may be possible without affecting yield, even in suboptimal soils with low water holding capacity (Stewart et al. 2011). However, such conclusions are not overwhelmingly conclusive as other studies have shown that high levels of stress may have a slight negative effect on yield (Dhillon 2015; Naor 2008).

To eliminate calibration drift difficulties that arose with the mobile sensor suite, and to decrease the necessity of visits to the field while improving the frequency of data collection, Upadhyaya et al. (2014) developed a continuous sensor suite (leaf monitor). The continuous nature of this data also made it a feasible tool for irrigation management. The leaf monitor detected plant stress in real-time via a close-range thermal infrared sensor in addition to measuring the microclimatic variables of air temperature, wind speed, photosynthetically active radiation (light) incident on a leaf, and relative humidity (Upadhyaya et al. 2014). The leaf monitor was attached to a node of a wireless mesh network, which permitted remote access of leaf temperature data in real-time via the web (Dhillon et al. 2013). With the data provided by the leaf monitor, the stress of the plant could be measured and the relationship between irrigation amount and timing explored. When combined with relatively homogeneous management zones, irrigation scheduling applied to a region of trees with similar characteristics can lead to a maximization of water use efficiency (Heerman et al. 1990). Previous work had demonstrated the relationship between a crop water stress index (CWSI) from leaf monitor data and deficit stem water potential (DSWP) in almonds, but this relationship had yet to be verified for the grape crop (Dhillon et al., 2014a). Additionally, while the leaf monitor had the potential to be used as an irrigation management tool, its feasibility as such had not been tested.

The objectives of this study were: (i) to monitor PWS by measuring leaf temperature and microclimatic variables using a continuous sensing system interfaced to a wireless network, (ii), to develop irrigation management zones based on soil and plant characteristics, and (iii) to verify the feasibility of implementing a variable rate, plant water stress based irrigation management scheme that accounts for spatio-temporal variability.

Methods

In the 2015 growing season, variable rate, deficit irrigation management based on proximal plant sensing in management zones was implemented in a 5 acre plot of almond trees at Nickels Soil Laboratory in Arbuckle, CA. The feasibility of the leaf monitor for precision irrigation management was evaluated in grapes in a 10 acre plot at E & J Gallo Vineyard in Galt, CA.

In order to properly account for spatial variability, homogeneous management zones were developed in the almond orchard as well as the vineyard to properly account for the water applied to a given tree/vine. Management zones were developed based on plant and soil characteristics in both crops. In almonds, the characteristics of digital elevation (obtained using RTK GPS units and a laser rangefinder), shallow (surface) electrical conductivity (EC), soil texture, leaf temperature and canopy cover (as measured by a UAV) were considered. A digital elevation map was obtained using RTK GPS units and a laser rangefinder at distinct points throughout the orchard. Similarly, leaf temperature measurements were made with a handheld sensor suite with an IR sensor to obtain the temperature of points throughout the orchard. These points were interpolated into a continuous map using kriging (Figure 1a). These maps were sampled at the location of each tree in the orchard and the corresponding data for each tree was input into an unsupervised fuzzy classification. In almonds, two clear management zones emerged- dictated primarily by digital elevation. In grapes, the plant and soil characteristics considered were digital elevation, soil texture, surface and subsurface EC (shallow and deep layers, respectively), yield, and NDVI (Landsat image). Similarly, kriging interpolation of discrete data points created continuous maps (Figure 1b). In grapes, two distinct patterns emerged that were subsequently combined to create two management zones. In this way, each management zone represented a relatively homogenous region within the orchard or vineyard. In almonds, each management zone had two treatments: plant water-stress based management and grower application where water management was managed entirely by the grower. In grapes, there were two treatments for deficit irrigation in addition to the grower application.

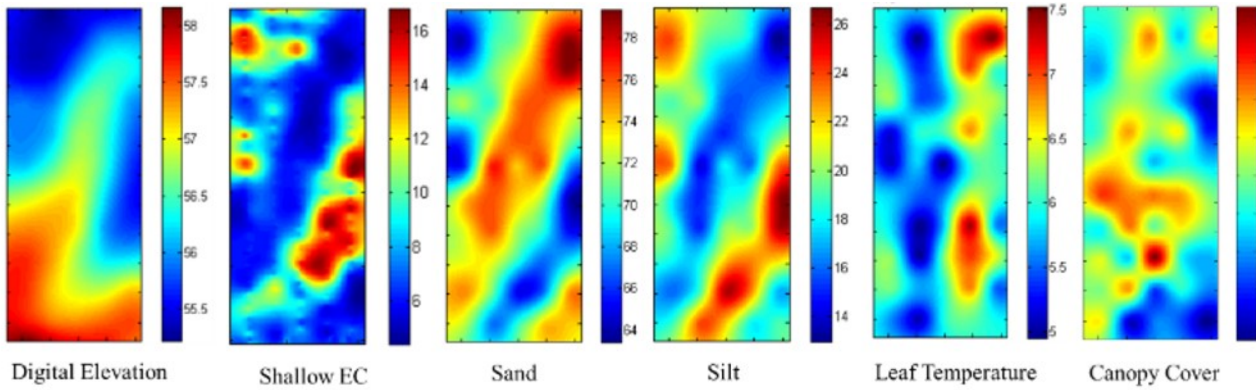


Fig. 1a From left to right: krigged maps of plant and soil characteristics in almonds: digital elevation, shallow EC, sand content, silt content, leaf temperature and canopy cover

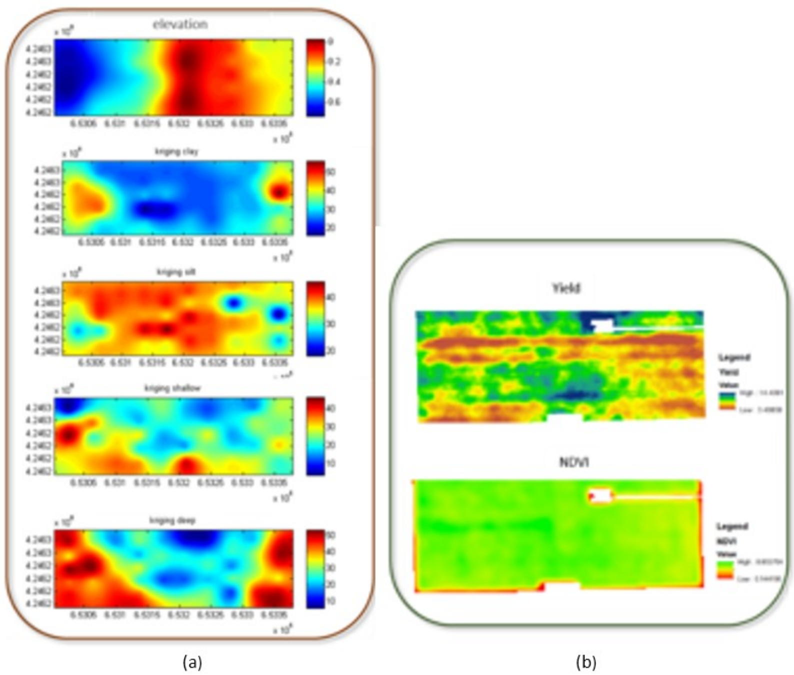
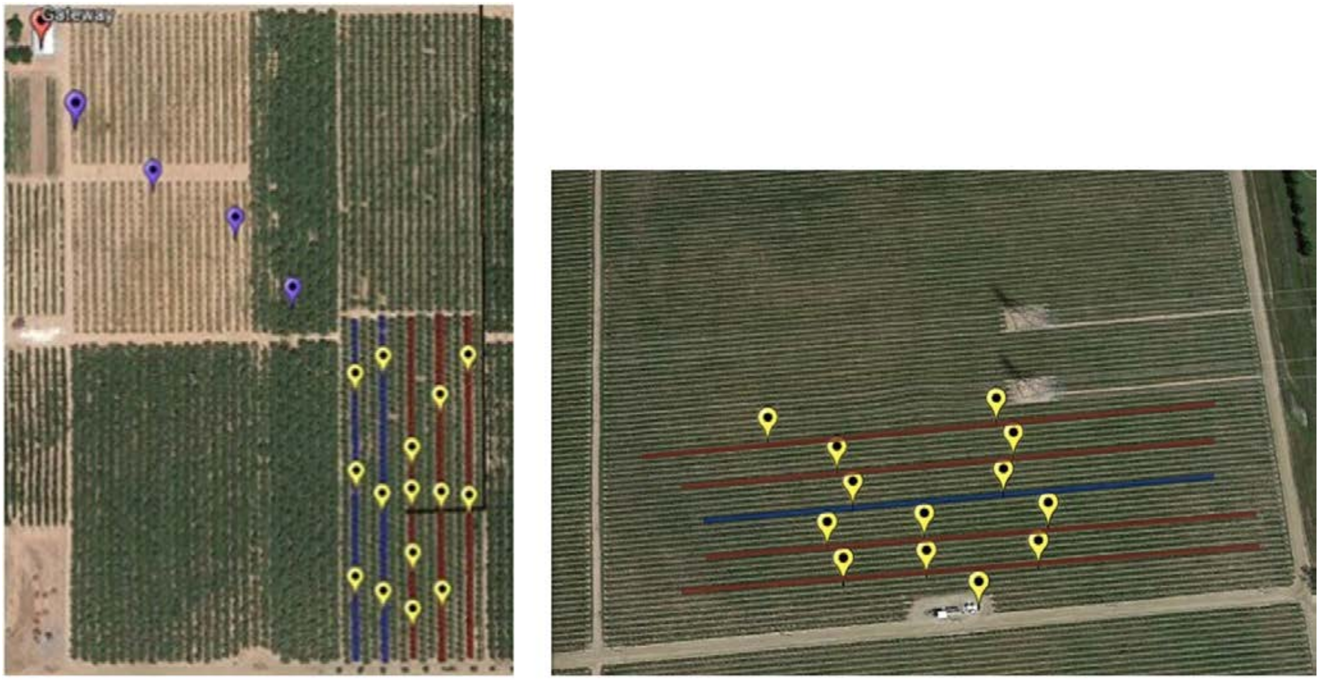


Fig. 1b From top to bottom: krigged maps of (a) soil characteristics of digital elevation, clay content, silt content, shallow EC, deep EC and (b) plant characteristics of yield and NDVI for determining management zones in grapes

Leaf monitors were installed in 14 selected trees in almonds and ten selected vines in grapes, including one saturated and one simulated dry control in each crop. Six leaf monitors were assigned to each management zone in almonds with three in grower treatment and three in PWS based irrigation treatment. There were two treatment groups in grapes; four vines experienced increasing water stress and four vines experienced decreasing water stress. The saturated control tree/vine had an extra drip line and received 50% more water than other trees/vines for each irrigation. The simulated dry control monitored a leaf with the stem broken. Leaf monitor tree/vine locations were selected based on representative SWP values for that management zone, as derived from SWP maps created on three different occasions. Each map consisted of 50 separate points which were combined to create interpolated SWP maps using either kriging (almond) or inverse distance (grape) techniques.

In both crops, real-time data regarding PWS was continuously received via a wireless network. In almonds, leaf monitors were interfaced to Eko Pro Wireless Sensor Nodes (Memsic Inc., Andover, MA) using a RS485 chip on a custom printed circuit board. Leaf temperature, air temperature, relative humidity, wind speed, and incident PAR measurements were made every 4 minutes and transmitted to the Eko Node gateway about every 15 minutes via a wireless mesh network.

Repeaters were used to extend the distance of the signal to reach the gateway. In grapes, leaf monitors and latching solenoid valves were interfaced with cellular network hubs (Cermetek Microelectronics, Milpitas, CA) which transmitted data every 15 minutes. Latching solenoid valves were separately controllable for each treatment within the orchard/vineyard in accordance with the management zones. Drip lines, pressure sensors, and soil moisture sensors were also installed according to these management zones. The final setup for both crops is seen in Figure 2.



(a) (b)

Fig. 2 Google Earth images of (a) node locations (yellow), repeater locations (blue), and gateway location (red) in almonds and (b) hub locations in grapes. In each, blue rows indicate grower treatment and red lines indicate PWS-based treatment

The relationship between SWP and a stress index based on measured variables was examined. Calculations of CWSI in almonds and modified crop water stress index (MCWSI) in grapes were made according to equations (1) and (2) presented below (Jackson et al. 1981; Dhillon et al. 2013). The MCWSI differed in that it used direct temperature of the saturated, observed, and simulated dry leaves as opposed to the difference between those temperatures and the ambient.

$$CWSI = \frac{(T_{Leaf} - T_{air})_{Obs} - (T_{Leaf} - T_{air})_{Sat}}{(T_{Leaf} - T_{air})_{Dry} - (T_{Leaf} - T_{air})_{Sat}} \quad (1)$$

$$MCWSI = \frac{(T_{Leaf})_{Obs} - (T_{Leaf})_{Sat}}{(T_{Leaf})_{Dry} - (T_{Leaf})_{Sat}} \quad (2)$$

Leaf monitor data was calibrated in order to correct for between-sensor variations in the data and to correct for natural differences between individual leaves; these differences would have caused discrepancies in the slope and intercept values between the leaf monitors on monitored trees/vines and those on saturated trees/vines. Leaf temperature sensors were calibrated based on differences between the saturated tree/vine and each individual tree/vine monitored. Air temperature sensors on monitored leaves were calibrated with respect to air temperature sensor on the simulated dry leaf. The monitored tree/vine leaf temperature values were calibrated to that of the saturated tree/vine leaf temperature one day after irrigation for an irrigation event that supplied enough water to all the trees to achieve saturation. In grapes, the slope and intercept of the saturated and the monitored trees were compared. Corrections were made for the intercept so that these curves matched data between 1-4 AM. In other words, it was assumed that leaf temperature equaled air temperature during wee hours of the night when leaves were not transpiring. Corrections of slope were made for data between 12-3 PM.

Comparisons with SWP measurements were made for verification of stress index accuracy. Midday SWP measurements were taken regularly one day after irrigation with a pressure bomb between the hours of 12 -2 PM for comparison with this stress index. DWSP values were also computed to account for differences in daily vapor pressure deficit.

From September 18th to 27th, leaf monitors in grapes were tested by subjecting vines to alternating periods of drying and of saturation to assess suitability of leaf monitor measurements in assessing PWS. A group of twenty vines (four blocks of five vines each) was subjected to a period of drying followed by a period of wetting to monitor grape response to decreasing amounts of stress; another group of twenty vines (four blocks of five vines each) was subjected to a period of saturation followed by a period of drying to measure grape crop response to increasing amounts of stress.

In almonds, irrigation decisions were made based on leaf monitor data in order to keep plant water stress within a reasonable range (about DWSP of 5 or less), or below a CWSI value of 0.3. Precision irrigation in almonds was implemented between July 25th and August 6th.

Results & Discussion

Irrigation management decisions were made based on PWS index values (CWSI) in almonds and the suitability for using MCWSI as an indication of PWS for precision irrigation management was evaluated in grapes. In each crop, two management zones were created to represent homogeneous zones within the orchard/vineyard (Figure 3). In grapes, two patterns emerged and two management zones were created based on a combination of these two patterns; the edge regions which did not belong to either management zone were treated the in same way as the neighboring regions (Figure 3). Soil properties in almonds, especially digital elevation, were particularly influential when two management zones were created. Comparison of Figures 1 and 3 highlights the relationship between final management zone determination and digital elevation. While each factor was equally weighted in the classification, this pattern may be due to the fact that digital elevation highly influences electrical conductivity. Still, the high variability found in all the soil properties analyzed suggest that the development of management zones could improve current irrigation practices.

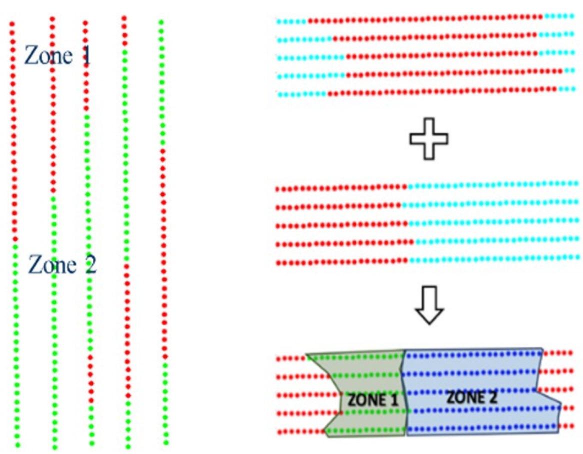


Fig. 3 Two management zones were created in almonds (left) and grapes (right). In almonds, circles represent one almond tree in the orchard; in grapes, circles represent a group of five vines. In grapes, the unsupervised fuzzy classification yielded two distinct patterns. These patterns were combined to create a single map consisting of two management zones (bottom, right)

The behavior of the PWS based irrigation treatment in each management zone was monitored with three leaf monitors. Temperature difference and CWSI plots over time were used to schedule the irrigation in almond crop. An example of the behavior of the two management zones in almonds over time (Julian days) is seen in the temperature difference (i.e. air temperature – leaf temperature) plot of Figure 4. In almonds, this period corresponds to July 25th – Aug 4th, 2015. When a tree transpires, its stomata open and a lower temperature is observed on each leaf's surface compared to the air. For a well-watered tree (green curves, top curve), this temperature difference is high; for a simulated dry tree (red curves, lowest curve), this difference is low. The behavior of the temperature difference for each monitored tree (blue curves, center) was observed with respect to that of a well-watered tree and a simulated dry tree. While temperature difference plots provided a qualitative understanding of the monitored zone's behavior compared to the saturated and dry controls, the CWSI plots provided a quantitative evaluation of the monitored vine's behavior and facilitated irrigation timing decisions.

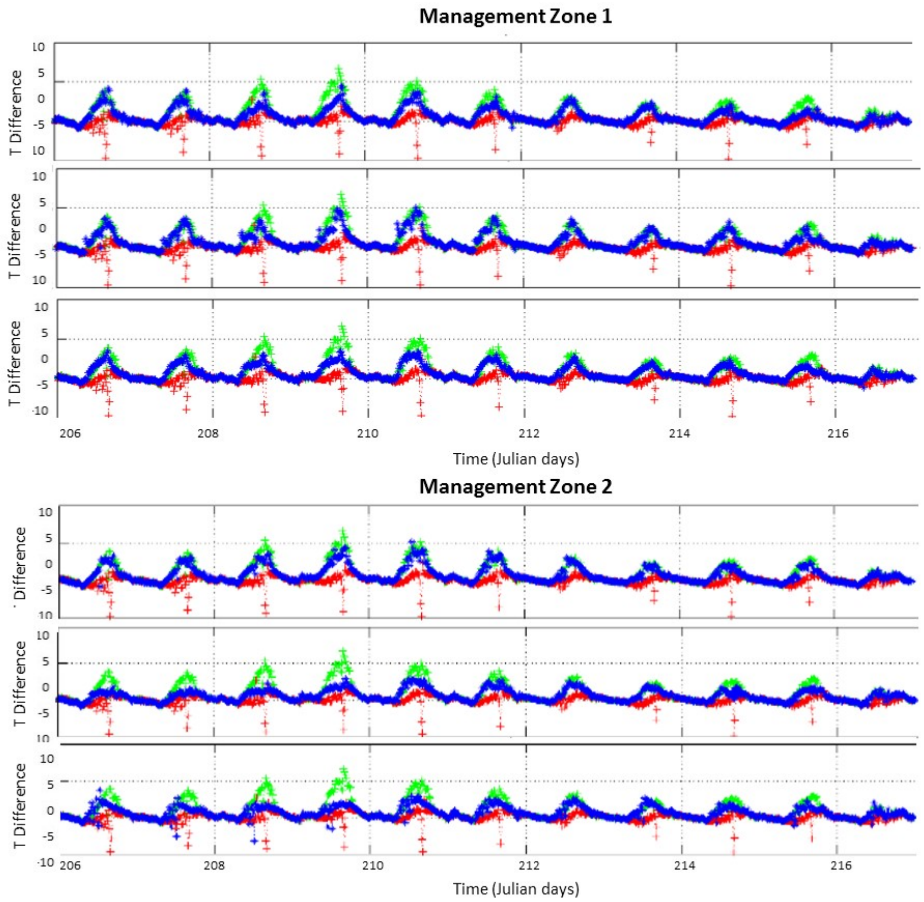


Fig. 4 Almond orchard data of continuous leaf monitor temperature difference plots between leaf and air temperature for the saturated (green-top curve), monitored (blue-middle curve), and simulated dry (red-bottom curve) trees in management zone 1 (top) and management zone 2 (bottom) for the PWS based irrigation treatment

Figure 5 shows the stress index (CWSI) response corresponding to the same dates for each management zone, for stress controlled and for grower treatments. A CWSI value of one corresponds to a dry tree and a CWSI value of zero corresponds to a well-watered tree. In almonds, the PWS based irrigation treatment showed a more continuous curve in plant stress when compared to grower management in the same region. It was also observed that on days with a particularly high VPD, trees subjected to deficit irrigation responded less strongly (smaller, less abrupt increase in water stress level) than those receiving full water by grower treatment (see Julian Day 208 in Figure 5).

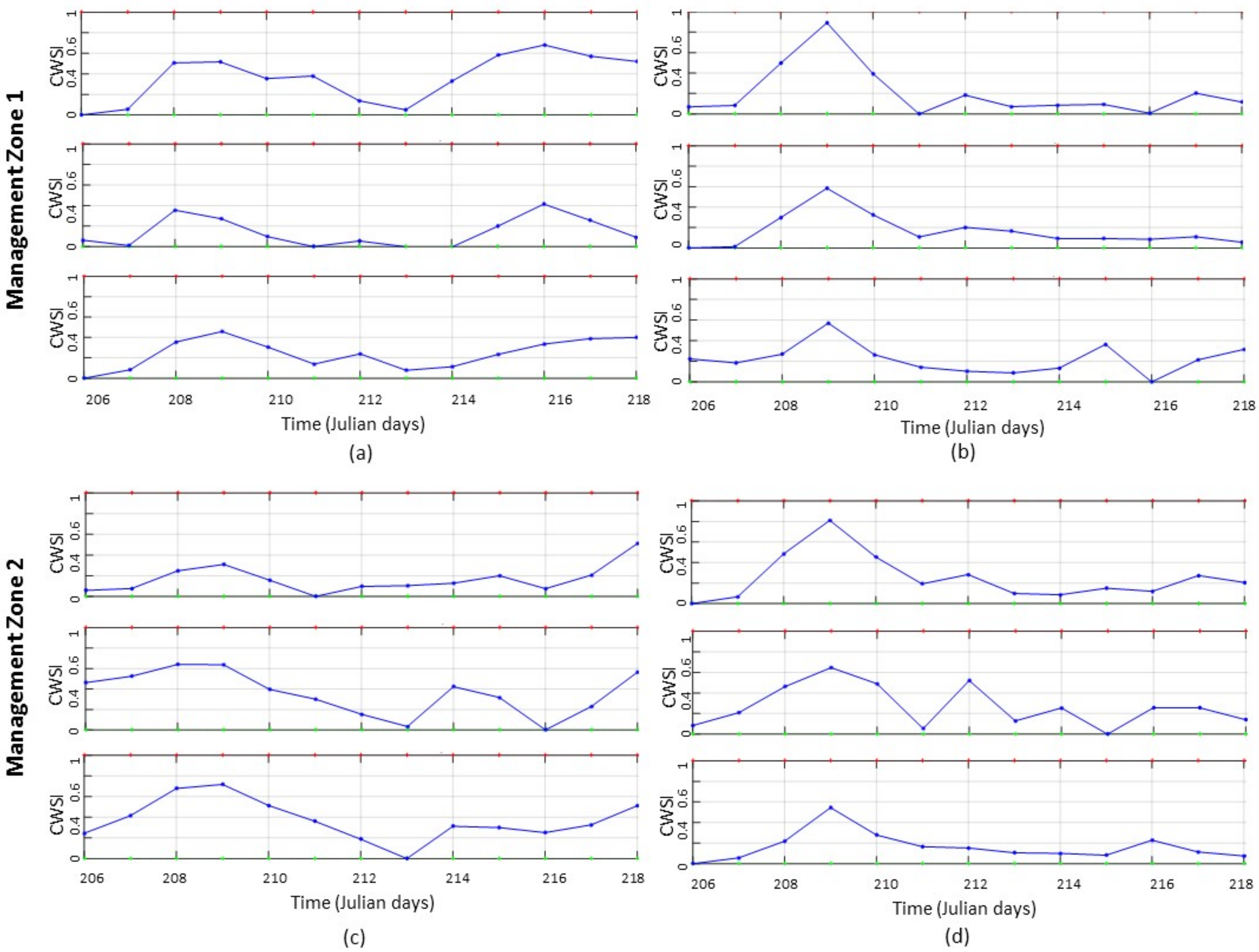


Fig. 5 In management zone 1, (a) PWS based irrigation management and (b) grower irrigation treatment CWSI values over time (in Julian days). In management zone 2, (c) PWS based irrigation management and (d) grower irrigation treatment CWSI values over time (in Julian days)

In almonds, both temperature difference and stress index plots were examined when considering irrigation, but the average CWSI values for each zone ultimately dictated irrigation decisions. When the average CWSI values for a zone exceeded the maximum allowable stress (CWSI of 0.3), irrigation was implemented at a defined percentage of ET. Figure 6 demonstrates how the applied amount of water was adjusted over time until desired stress level was achieved and maintained in each management zone. It was found that the management zones required very different amounts of water in order to maintain their average water stress within a reasonable range. An initial amount of deficit water (85% of ET) was applied for each zone for the first irrigation. Zone 1 remained within a reasonable range of PWS with this amount of water and eventually was satisfied with 80% of ET. For Zone 2, the initial amount of water was insufficient to maintain plant water stress level within a reasonable range (i.e., a CWSI value of 0.3 or lower). The amount of water applied was increased until the plant water stress level came under control; this amount corresponded to 110% of ET in Zone 2. These trends in irrigation amount and timing are shown in Figure 6. In terms of grower's practice, these results translate to about 70% of the water applied by the grower in management zone 1 and about 90% water compared to the grower treatment in zone 2. The relationship between DSWP and PWS was confirmed in almonds. A second order relationship between CWSI and DSWP was found with an R^2 value of 0.79, evaluated from average values for each treatment of each management zone (Figure 9).

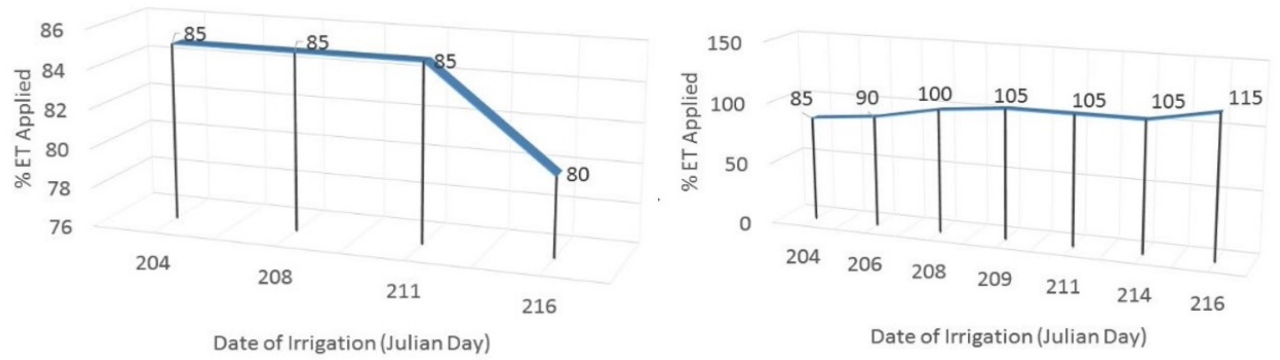


Fig. 6 The irrigations in the almond crop in management zone 1 (left) and zone 2 (right) over time (in Julian days) as a percentage of ET are shown as vertical lines. Zone 2 required more water and more frequent irrigations than Zone 1 in order to keep its PWS within a reasonable range (average zone CWSI less than or equal to 0.3)

An example of the stress index (MCWSI) in grapes over time is seen from September 18th- 27th, 2015 in Figure 7. Two canonical examples of increasing stress and decreasing stress plots are shown. Figure 7 and demonstrate that stress developed after just a few days and that vines required several days to recover from stress when subjected to a period of wetting. These data were used to analyze the behavior of grape crop PWS and compare the MCWSI values to DSWP. A linear relationship was observed between PWS as measured by MCWSI obtained with the leaf monitor and DSWP in grapes with an R^2 value of 0.70 (Figure 8). However, in this plot there are two points which appear to be outliers.

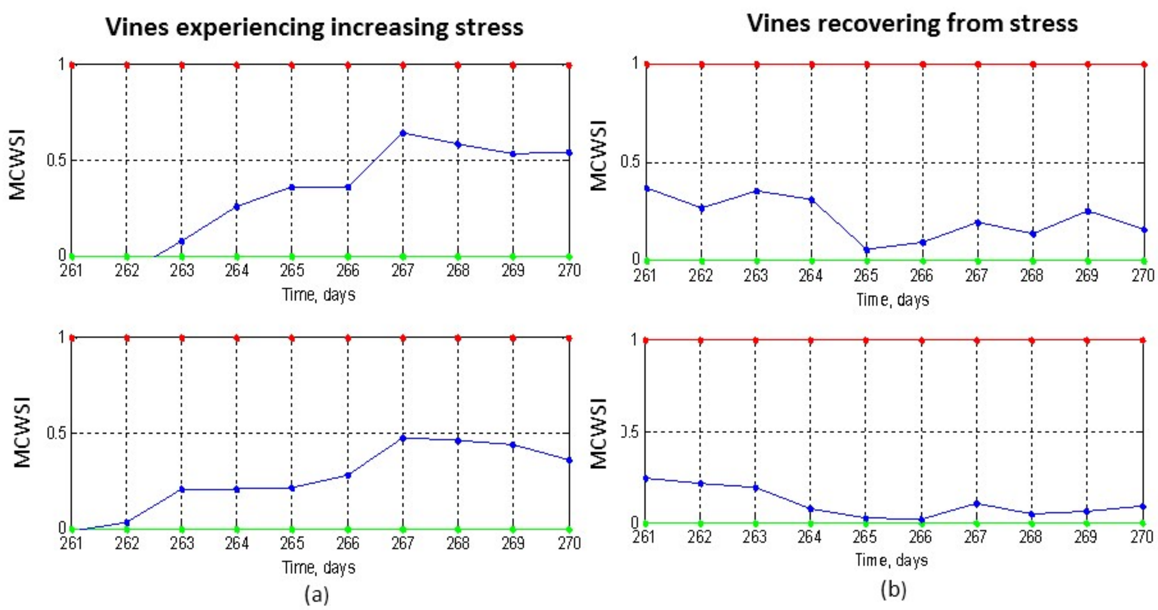


Fig. 7 MCWSI values from leaf monitor data over time (in Julian days) as a measure of PWS in grapes for (a) vines experiencing increasing amounts of stress following saturation, and (b) vines recovering from stress through full irrigation (i.e., saturation). An MCWSI value of 1 corresponds to a monitored vine behavior with high stress (i.e., dry); a value of 0 corresponds to an unstressed vine (i.e., a saturated vine)

Both suspect points corresponded to vines which had been subjected to a two week period of drying and which were recovering with daily irrigations. Environmental effects of daily vapor pressure deficit were accounted for in the DSWP value. In the temperature difference plots of Figure 8, it is expected that vines show stress initially followed by continuous recovery. However, leaf monitor #5 showed an abnormally low level of water stress in the DSWP measurement. The temperature difference plot shows that the vine was indeed stressed (a marked difference from the saturated vine), as expected. The second likely outlier showed a sporadic decline for DSWP over time for leaf monitor #9. The temperature difference plot shows a steady decrease in the amount of water stress seen in the vine, as expected for a vine recovering from stress. However, DSWP measurements suggest the vine was highly stressed on day 261, recovered completely on day 264, and then returned to a high stress level on day 266, which is highly unlikely (Figure 8 (b)). If these two points are removed, the relationship between MCWSI and DSWP improves significantly to an R^2 value of 0.82 (Figure 9). Implementation of precision irrigation management in grapes was left for the 2016 growing season.

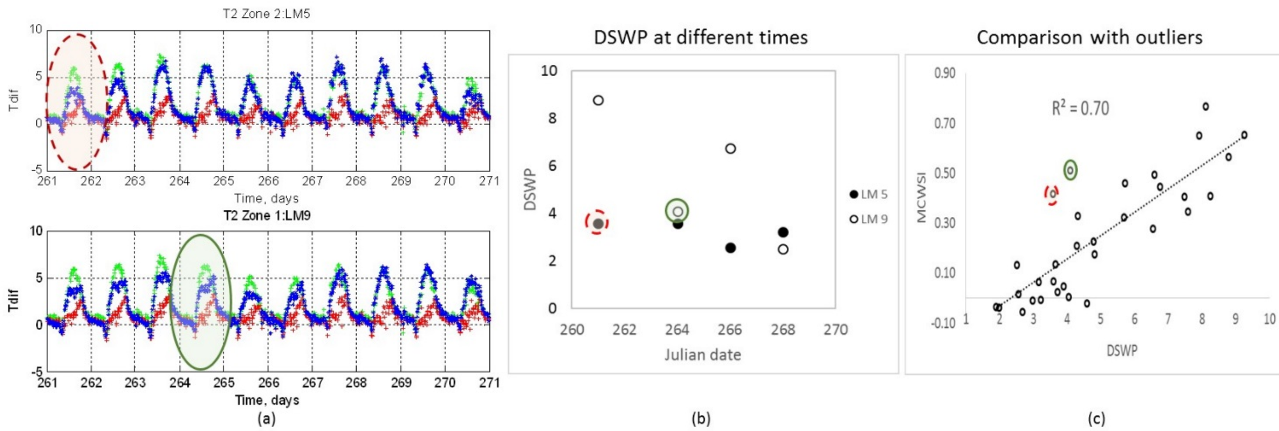


Fig. 8 Outlier analysis of (a) temperature difference plots over time (in Julian days) as vines recover from a period of water stress for leaf monitor #5 (top) and leaf monitor #9 (bottom); (b) DSWP over time as measured with a pressure chamber for leaf monitor #9 (open circles) and for leaf monitor #5 (closed circles); (c) DSWP values compared with MCWSI measurements obtained from leaf monitors yielded an R^2 value of 0.70 with suspected outliers

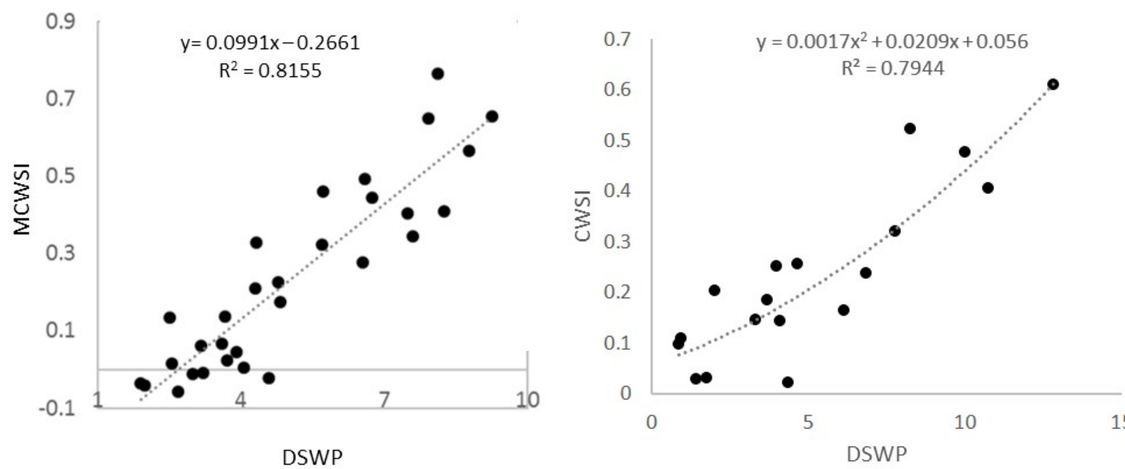


Fig. 9 (Left) A linear relationship is observed between MCWSI and DSWP in grape crop with an R^2 value of 0.82. (Right) A quadratic relationship is observed between CWSI and DSWP in almond crop with an R^2 value of 0.79

Both crops demonstrated temporal variability in PWS for different management zones. These results suggest that the behavior of the water stress indices developed used in conjunction with the management zones could be a useful tool for irrigation management decisions.

Conclusions

Two field-scale plots, an almond orchard in Arbuckle, CA and in a vineyard in Galt, CA, were divided into two management zones each based on plant and soil characteristics. PWS was evaluated by monitoring leaf temperature and microclimatic variables using leaf monitors interfaced with a wireless network in both crops. From these data, a stress index was estimated using a saturated (well-watered) and simulated dry (broken leaf) control. MCWSI was found to represent PWS well in grapes and displayed a linear relationship with DSWP with an R^2 value of 0.82. The relationship between CWSI and DSWP in almonds was confirmed with a quadratic relationship and an R^2 value of 0.79. This suggests these indices provided a reliable quantification of PWS. In almonds, irrigation management was implemented for a brief period of time. This system has the potential for significant water savings in almonds; however, data were acquired over a relatively short period of time and therefore the numbers obtained in the 2015 growing season are preliminary and should be regarded as such. Initial results indicate that management zone 1 required about 70% water compared to grower treatment and zone 2 required about 90% water compared to grower treatment.

Acknowledgements

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References

Anderson M, Kustas, W. (2008). Thermal remote sensing of drought and evapotranspiration. EOS Transactions of the American Geophysical Union, 89(26), 233-240.

Dhillon, R., Rojo, F., Roach, J., Coates, R., Han, C., Upadhyaya, S. et al. (2013). Development and Evaluation of a Leaf Monitoring System for Continuous Measurement of Plant Water Status. In Transactions of the ASABE- Paper number: 131596776. American Society of Agricultural and Biological Engineers. St. Joseph, MI.

Dhillon, R., Udompetaikul, V., Rojo, F., Roach, J., Upadhyaya, D., Slaughter, D. et al. (2014a). Detection of plant water stress using leaf temperature and microclimatic measurements in almond, walnut, and grape crops. Transactions of the ASABE, 57(1), 297-304. St. Joseph, Michigan: ASABE.

Dhillon, R., Rojo, F., Roach, J., Upadhyaya, S. and Delwiche, M. (2014b). A continuous leaf monitoring system for precision irrigation management in orchard crops. *Journal of agricultural machinery science*, 10(4), 267-272.

Dhillon, R. S. (2015). *Development and Evaluation of a Continuous Leaf Monitoring System for Measurement of Plant Water Status* (thesis).

Heerman, D.F., Martin, D.C., Jackson, R.D. and Stegman, E.C. (1990). Irrigation scheduling controls and techniques. In B.A. Stewart and D.R. Nielson (eds), *Irrigation of Agricultural* Crops. Agronomy Monographs No: 30 (pp. 509-53). Madison, WI: ASA, CSSA, and SSSA.

Howell, T. A. (1996, November). Irrigation scheduling research and its impact on water use. In Evapotranspiration and irrigation scheduling- Proceedings of 3rd international conference (pp. 21-33).American Society of Agricultural Engineers. St. Joseph, MI.

Jackson, R. D., Idso, S. B., Reginato, R. J., & Pinter, P. J. (1981). Canopy temperature as a crop water stress indicator. *Water resources research,*17(4), kl1133-1138.

Jones, H. G. (2004). Irrigation scheduling: advantages and pitfalls of plant-based methods. *Journal of experimental botany*, *55*(407), 2427-2436.

Lampinen, B., Sibbett, S., Olson, W., & Shackel, K. (1999). The relation of midday stem water potential to the growth and physiology of fruit trees under water limited conditions. Proceedings of the 3rd International Symposium on Irrigation of Horticultural Crops (pp.537).

Levitt, J. (1980). *Responses of plants to environmental stresses*, Chapters 1-2. New York: Academic Press.

Maupin, M., Kenny, J., Hutson, S., Lovelace, J., Barber, N., Linsey, K. (2010) Estimated Use of Water in the U.S.in 2010 (2014). Reston, VA: U.S. Dept. of the Interior, U.S.G.S. http://dx.doi.org/10.3133/cir1405. Accessed 15 March, 2016.

McCutchan, H. and Shackel K. (1992). Stem-water potential as a sensitive indicator of water stress in prune trees. *Journal of the American Society of Horticultural Science*, 117(4), 607-611.

Naor, A. (2008). Water stress assessment for irrigation scheduling of deciduous trees. *Acta Horticulturae*, 792.

Phene, C. J., Itier, B., & Reginato, R. J. (1990). Sensing irrigation needs. In Visions of the future-Proceedings of the 3rd National Irrigation Symposium-ASAE. Pub. 4-90. (pp. 429-443). American Society of Agricultural Engineers.

Stewart W, Fulton A, Krueger W, Lampinen B, Shackel K. (2011). Regulated deficit irrigation reduces water use of almonds without affecting yield. *California Agriculture,* doi: 10.3733/ca.v065n02p90.

Upadhyaya, S. K., Dhillon, R., Roach, J., & Rojo, F. (2014). System and methods for monitoring leaf temperature for prediction of plant water status. U.S. Patent no. 2014/0326801 A1. Date issued: May 21, 2014.