Whole Tree ET Responses to Mind and Moderate Water Stress

Project No.: HORT22.Shackel

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Summary

The long term objective of this research is to determine the responses of almond to water stress, and how irrigation management can be used to achieve the best balance between the negative and the positive consequences of these responses for crop productivity. Two short term objectives of this study are to accurately measure almond evapotranspiration (ET) using a weighing lysimeter (the ET "gold standard"), and to determine how ET is influenced by water stress. The irrigation standard for expressing ET is a crop coefficient (K_c), and the current almond board recommendation is that the K_c for a mature almond orchard at mid-summer is 1.17. A consistent finding through year 6 of this study is that almond K_c develops more quickly over the early years of an orchard than previously thought, and can be much higher than previously thought for a mature orchard. In 2020 (year 6) we have found midsummer K_c to be slightly over 1.3, and since the canopy shaded area is still below 80% (considered mature for almonds), this value may continue to increase in the future. Based on this Kc, the total calculated nonpareil ET for 2020 was 58 inches from March 1 – November 1, but because water was managed allowing some stress, particularly at hull split and harvest, the total water applied in 2020, including irrigation and rainfall, was only 48.8 inches. Nonpareil yields in the current study have also steadily increased over time and reached over 3,100 pounds nutmeats per acre (45 pounds per % PAR) in 2020. Hence, applying less than full ET does not preclude achieving high yields in almond. One important finding in 2020 was evidence that tree water stress is low and water use is high for the first 2 days following an irrigation, but that water stress, and substantial reductions in water use, can develop rapidly after this, at least for the soils at this site. The reduction in water use demonstrates that plants are responding to stress by limiting water loss, but whether this response will have a positive or negative effect on short- or long-term orchard productivity is not clear. Measurements from three commercial automated plant water stress sensors (FloraPulse, Saturas, Phytech) were compared to pressure chamber measured SWP on the lysimeter tree and an additional nonpareil tree for all sensors, and an additional 7 trees for the Phytech sensor. There was general relative agreement between each sensor and SWP, with the Phytech dendrometer being the most responsive to short term stress and irrigation events, but potentially without a sufficient measurement range for the full range of stress that occurs during hull split and harvest in almond. Both the FloraPulse and Saturas sensors were similar in their ability to measure across a range of SWP that can be expected in commercial almond orchards, but exhibited an uncertainty range of ±8.4 bars and ±6.0 bars, respectively, compared to SWP . The Phytech sensor also measures the rate of trunk growth, and this may be useful in determining when trunk growth has stopped and bark may be more resistant to injury from shaking.

A. Objectives

1) Compare measured ETc of the lysimeter tree to current ETc estimates based on canopy shaded area.
2) Quantify the reduction in ETc that is associated with deficit irrigation and lower SWP values.
3) Test candidate methods for automated measurement of SWP or other key plant responses to water stress.

4) Evaluate the accuracy of modeling and other remotely-sensed technologies for the measurement or calculation of ETc.

5) Test for a relation between irrigation, trunk growth, and shaker injury, as well as candidate methods to prevent ceratocystis infection when damage occurs, and methods to check bark strength before shaking.

B. Annual Results and Discussion

The measured 'actual' evapotranspiration (ET_a) from the lysimeter, and the resulting crop coefficients (K_a) in 2020 were generally higher than in 2019, with 'average' maximum K_a values of slightly over 1.3 in 2020 (Fig. 1) compared to less than 1.2 in 2019 (previous report). Note that the proposed almond K_c has not been drawn through the maximum observed values on any particular date, but rather through the average value during periods when K_a was generally high. A more detailed discussion of this issue will be presented below, but even during periods when K_a was generally high, a substantial day-to-day range (about 20%) in K_a could be observed. For example, jumping from 0.9 to over 1.1 in one day, and back to 0.9 the next, following a light irrigation in mid-April (Fig. 1). It is well known that individual daily values of ET_a and K_a are subject to variation due to many factors, including uncertainty in the lysimeter measurement system itself as well as uncertainty in the reference evapotranspiration (CIMIS ET_o) that is used to calculate K_a. Later in this report we will present evidence that there is very little uncertainty in the lysimeter measurement. Another factor that is typically associated with day-to-day variation in K_a is higher rates of soil evaporation immediately following each irrigation event. Most irrigations were applied during the day, and because the lysimeter tree is irrigated with the same system as the rest of the nonpareil trees, this disturbs the lysimeter weight and prevents calculation of a K_a on the date of irrigation. Most irrigations lasted about 24h however, and the surface soil remained wet for 1-2 days following each irrigation, so soil evaporation should also have occurred at that time. Eliminating soil evaporation by covering the soil surface with a plastic tarp, however, had no influence on the day-to day variation observed in K_a before or after irrigation events (Fig. 1 covered conditions). These results are consistent with previous years reports, and indicate that, at least for the irrigation system used (double line drip) and soil conditions (Dinuba fine sandy loam) at this site, soil evaporation is negligible. Hence, our current hypothesis is that these day-to-day changes in K_a reflect physiological responses of the tree to water stress (see below for further discussion of results related to stress).

In order to make an accurate comparison between eddy-co and lysimeter data over time, only dates when both measurements were present (i.e., when the lysimeter weight was not disturbed by irrigation, rain or other events) were used. In 2020, the time-smoothed eddy-co and lysimeter measured K_a were very similar in both pattern over time as well as the level at any given time (Fig. 2). Because the eddy-co method measures the effective K_a over a much larger area than the individual lysimeter tree, it is important that the lysimeter tree have a canopy size that is similar to the other trees in the block. Trunk diameter measurements were used as an indirect indicator of canopy size in the early years of this project, but a more direct estimate of canopy size (shaded area, PAR) was obtained using drone photogrammetry in 2020. This estimate showed that the lysimeter tree was highly representative of the most common size of its variety in the orchard (Fig. 3). This is consistent with the overall agreement between the eddy-co and the lysimeter measured K_a (Fig. 2), although it should be noted that the eddy-co estimate should also include the contribution from the pollinizer varieties. The stature of one of the pollinizers (Wood colony) is substantially smaller than the nonpareil and the other pollinizer (Monterey), and in addition, the pollinizer rows are irrigated at about 70% of the rate of the nonpareil. The reason for the differential in irrigation, which began in 2018 (year 4), was to favor the canopy development, and presumably yield, of the main variety (nonpareil).

The ET requirements of a young almond orchard must be calculated based on published values of K_c for a mature almond orchard and the relation between immature canopy size and immature K_c. The current almond board recommendation (https://www.almonds.com/sites/default/files/content/attachments/irrigation_scheduling_using_evapotranspiration.pdf) is for a maximum mature K_c of 1.17, which has been rounded to 1.2 for the purposes of comparison. Based on a review by Sammis et al (2004) the mature K_c should occur at a canopy size of about 60% PAR or more (Fig. 4, dashed black line). In addition to finding K_a's in excess of this estimate as early as year 3 of this study, lysimeter measurements have also shown a much larger increase in K_a from 5 to 40% PAR than expected, as well as a continued increase from 40% to 70% PAR (Fig. 4, almond lysimeter), rather than a maximum value at or above 60% PAR. A recent study of Drechsler et al. found a similar K_a for young orchards (around 20% PAR), but much lower maximum levels of K_a as PAR increased (Fig. 4, dashed grey line). In view of the overall agreement found between the lysimeter and an independent method (Fig. 2), it appears that current estimates of K_c in almond are underestimates, perhaps substantially. It is important to recognize that a valid K_c for any crop must be based on confirming that the crop is fully active and not experiencing a limitation in water availability. The well-known reason for this assumption is that in essentially all crops, water use declines when plants experience water stress, due to a number of physiological responses, mainly stomatal closure. Consistent with previous reports, this has been clearly documented to occur in almonds, especially when water is withheld during hull split and harvest, for instance in the low values of K_a (0.8 and less) recorded in July/August of 2020 (Fig. 1). A consistent reference state condition of high water availability for the purposes of determining almond K_c however, does not imply that almonds should be maintained in this state in order to achieve maximum economic productivity. Based on the proposed K_c shown in figure 1 and CIMIS weather data for 2020 from March 1 – November 1, the total calculated ET for 2020 was 58 inches. However, the total water applied in 2020, including irrigation and rainfall, was 48.8 inches. Nonpareil yields in the current study have steadily increased over time (Table 1), and reached over 3,100 pounds nutmeats per acre in 2020, despite the fact that water has routinely been withheld, and SWP and K_a have declined at hull split and harvest each year. A key overarching objective of this research is to determine the physiological responses of almond to water stress, and how irrigation management can be used to achieve the best balance between the negative and the positive consequences of these responses for crop productivity.

Irrigation was reduced in mid-July for hull split and there were clear patterns in K_a and SWP over each irrigation cycle during this time (Fig. 1, Period A). A detail of this period showing five irrigation events are presented in figure 5. Each irrigation event can be seen as an increase in lysimeter weight and a missing value for K_a on the day of irrigation (Fig. 5, top panel). K_a was close to the proposed K_c (about 1.35) for 2-3 days following each irrigation, but declined rapidly thereafter, dropping to values at or below 1.0 (Fig. 5, top panel). It should be noted that these day-to-day changes at the end of each irrigation cycle are even larger than the substantial day-to-day changes noted for figure 1. For the first complete drying cycle shown in figure 5 (July 13-17), pressure chamber SWP measurements were made 1, 2, and 4 days after irrigation, and for these dates the baseline SWP remained in a very narrow range (from -8 to -9 bars, Fig. 5, bottom panel). SWP was about 3 bars dryer than baseline on day 1 and declined to 4 bars drier on day 2, but substantially declined to 14 bars drier than baseline by day 4 (Fig. 5, bottom panel). Even though they were not collected daily, all of the periodic pressure chamber SWP measurements shown in figure 5 show the same pattern: 3 to 4 bars drier than baseline at the start of the irrigation cycle and 10 to 14 bars drier than baseline at the end. However, an advantage of the automated sensors is that they collect daily readings, and for the period shown in figure 5, the Phytech sensor showed the most consistent response to irrigation, with a marked increase in value on the day of irrigation (day that lysimeter weight showed an increase) in every case (Fig. 5). FloraPulse had a data gap for the first irrigation date (July 13), but typically showed a smaller response or a response delayed by about 1 day to each irrigation, and the Saturas sensor showed a consistent 1 day delay, in addition to showing a pattern of increasing stress from the day before irrigation extending to the day of irrigation (Fig. 5). It should be emphasized that the response time of a sensor is only one factor in determining whether the sensor will be useful for irrigation management. The consistency in sensor response over time, and the relation of the sensor reading to the physiological responses of the tree may be of equal or greater importance than the speed of sensor response. An analysis of this consistency over the entire trial will be presented below. For the hull split period shown in figure 5, the overall trend of all sensors was similar on a relative basis: all showed stress and recovery during the 5 day irrigation cycles (July 10 – 22), and an overall pattern of recovery when irrigation was increased (July 23 – August 1).

The recommended level of midday SWP for the hull split period shown in figure 5 is -14 to -18 bars, but this was difficult to achieve due to the rapid decline in SWP that occurred at the end of each 5-day irrigation cycle. A rapid decline also occurred in K_a, and in order to better understand the physiological factors involved in this decline, a detailed analysis of the daily pattern in whole tree ET was performed. Data was combined from the three longest irrigation cycles shown in figure 5, and for the first 2 days following irrigation, showed a remarkable divergence in the daily pattern of ET_a and ET_o (Fig. 6, days 1 and 2). Up to about noon, ET_a and ET_o were almost identical, but this was followed by a progressive increase in ET_a compared to ET_o until about 18:00 h PST, when the difference between the two remained approximately constant (Fig. 6, days 1 and 2). The very small error bars and almost identical values for the ET_o values on both days indicate that daily pattern of evaporative demand across all 6 days in question was essentially identical. Error bars for ET_a indicated somewhat more variation, but were also surprisingly small, given the fact that they are based on 10 minute averages, compared to the hourly averages for ET_o. This consistency, as well as the close match with ET_o before noon, is strong support for the claim that this lysimeter is both accurate and precise, and that ET_o is a reasonable measure of almond canopy water loss, at least until about noon. It should be noted that the CIMIS weather station for calculating ET_o is located at the same field station as the lysimeter. By day 4 after irrigation, as well as for the individual day 5, there was a close match between ET_a and ET_o throughout the day, with day 3 being intermediate (Fig. 6). A reduction in ET_a relative to ET_o, especially one that is reversible and occurs over a few days, must be due to physiological changes in the almond tree, in this case, presumably stomatal closure. We have already shown (previous reports) that stomata close more-or-less in proportion to the degree of stress (SWP) experienced by the tree, but we now have whole-tree evidence that this closure can begin within a few days after irrigation. It must be emphasized that it is too soon at this point to conclude that this closure will have a negative impact on crop productivity, but it is reasonable to assume that it will have some physiological consequences for the tree. Another important result from this analysis is that the daily pattern in the rate of water loss following irrigation is very different than expected based on ET_o, as illustrated in figure 7. It is typically assumed that energy from sunlight is the primary environmental factor driving evaporation from canopies, which is why the peak in ET_o (Fig. 7, middle panel) occurs at about the same time as the peak in solar radiation (Fig. 7, top panel), rather than at the peaks in temperature and air vapor pressure deficit (Fig. 7, top and bottom panel, respectively). However, for days 1 and 2 after irrigation, peak ET_a occurred at 15:00, 2 hours after peak ET_o (Fig7). It is interesting to note that other researchers have found a relatively high temperature optimum for photosynthesis in almond (about 37C, Nico Bambach, personal communication), and hence it may not be surprising that stomata would continue to open, and photosynthesis increase, as temperature increased from about 34C at 13:00 to 35 C at 15:00 h (Fig. 7, top panel). Of course, this would only be expected when water was not a limiting factor, which appears to be the case for the first 2 days after irrigation in this soil.

Figure 5 summarizes the ET_a of each date as a single value of K_a, and K_a exhibited a very similar pattern over time in each of the three 5-6 day irrigation cycles (July 13-17, 18-22, and July 30-August 4). Namely, a relatively high K_a on day 1, a slight increase on day 2, a slight decrease on day 3, then a more dramatic decrease on day 4. However, based on the ET_a curves, the net decrease from day 2 to 3 was also associated with a marked increase in variability (Fig. 6). The ET_a variability on day 3 may have been largely due to environmental variation (error bars for ET_o also increased), but ET_a variability persisted to day 4 even though ET_o had returned to relatively low variability (Fig. 6). Deficit irrigation in almonds typically results in higher levels of tree-to-tree variability in the orchard, presumably because each tree is responding to local conditions of water availability. The data of figure 6 indicates that the same principle may apply to a single tree as it responds to uneven water availability over the irrigation cycle. For instance, on July 16 (day 3 of the first irrigation cycle) the total lysimeter weight (an accurate mass-balance estimate of the entire root system moisture content) was slightly higher than the total weight on July 20 (day 2 of the second irrigation cycle), even though K_a on July 6 was declining and K_a on July 20 was maximum. Hence, the difference in K_a was not associated with total root system water availability, but presumably by local water availability. A key question in using irrigation to manage water stress is determining the frequency and amount of water required to maintain the trees at a target level of stress. These data suggest that for this soil, a high frequency of limited water application, perhaps even targeted to a specific period in the day, may be worth testing in the future. Continuous monitoring of tree water stress will be an important enabling technology in this effort, although it should also be recognized that SWP can be measured manually at any frequency, so in this case, obtaining reliable, accurate information on SWP is not limited by lack of an appropriate technology.

K_a values during the harvest period (Period B, Fig. 1) reached values as low as 0.3, and all sensors indicated substantial levels of water stress during this time (Fig. 8), at least up to the date of shaking (August 14, 2020). The lysimeter tree and an adjacent nonpareil tree, which were both instrumented with all sensor types, were harvested manually in order to avoid potential damage to the lysimeter as well as the sensors from shaking. An additional 7 trees in the orchard were instrumented with Phytech dendrometers, and these sensors were removed prior to shaking and re-installed after shaking, which may explain the unusual plant status behavior around this time (Fig. 8, after August 14), although the undisturbed phytech sensors also showed a decrease in stress on August 17, when the lowest K_a was recorded and both FloraPulse and Saturas sensors were indicating increasing stress. The overall trend in both FloraPulse and Saturas sensors throughout the period shown in figure 8 was also very similar. Both showed a temporary recovery from the August 18 irrigation, and a larger recovery from the larger August 25 irrigation (Fig. 8). By September 2, pressure chamber measured SWP had recovered to close to the baseline and K_a had recovered to close to the proposed K_c, although the Saturas and to some extent FloraPulse sensors were still indicating a progressive recovery after this, possibly showing the same delay in response to irrigation as was mentioned for period A.

Deficit irrigation around harvest (Period B, Fig. 1), resulted in large reductions in K_a below the proposed K_c, and because these reductions are presumably due to reductions in stomatal opening, K_a reductions should serve as a whole tree 'gold standard' measure of physiological stress. Only five SWP measurements (generally targeted at the beginning or end of an irrigation cycle) were available during this time, but for these measurements there was a very strong linear relation between SWP reductions from baseline and K_a reductions from K_c (Fig. 9, pressure chamber). It is important to note that the observed reduction in K_c for a 10 bar reduction in SWP was about 0.6 (Fig. 9), intermediate between the 0.7 reduction found in this project in 2019, and the 0.5 reduction found for peaches by Johnson et al. (2005), also using a lysimeter. For these same five dates, both the Saturas and FloraPulse sensor had essentially the same strong linear relation as the pressure chamber, whereas the relation for the Phytech sensor, even though it did show the same trend, was not statistically significant (Fig. 9, black dots on graphs, and fit line). The statistics relating K_a reductions to reductions from baseline measured by either the pressure chamber, FloraPulse, or Saturas sensor was essentially the same when considering dates when data from all sensors was present, with highly significant r-squares and relatively narrow uncertainty in the K_c reduction at a given level of stress (Fig. 9, inset table). R-squares were lower and uncertainty increased when all available data was considered, with the FloraPulse sensor showing the highest r-square and lowest uncertainty (Fig. 9, inset table). It is not clear if a similar reduction in r-square and increase in uncertainty would also have occurred for the pressure chamber if daily measurements had been made, and this should be confirmed with further study. It is possible that the relation between K_c and any physiological measure of water stress will be less well defined when trees are recovering from stress, especially if severe stress is associated with a slow response of stomata when stress is relieved. For instance, the Phytech sensor recorded a large reduction in water stress after irrigation on August 25 followed by increasing stress from August 26-28, even though K_a continued to increase from August 26-28. A better understanding of these processes will improve our ability to utilize any water stress sensor, including the pressure chamber, most effectively for irrigation management.

A similar statistical analysis to that shown in figure 9 was performed for the relation of K_a (with and without adjustment for K_c) to all sensor readings (with and without adjustment for the SWP baseline) for periods A and B as well as for periods outside of these times. This analysis (not presented) was consistent with the analysis shown in figure 9 in terms of comparing sensors, but was never as statistically significant as that shown in figure 9. Based on the fact that pressure chamber measured SWP is generally regarded as reliable measure of physiological stress however, a correlation analysis of all sensor data for various periods of time was conducted and is presented in Table 2. Similar to the statistics in figure 9, the highest r-square values and lowest uncertainties were found in period B, but all sensors, including Phytech, were found to have a statistically significant correlation to pressure chamber measured SWP from May through October (Table 2). These results support further testing of these sensors for use in irrigation management, with the understanding that each sensor may have its own limitations. The Phytech sensor appears to be the most responsive to irrigation events, and the most sensitive to mild levels of stress, but may not have a sufficient range to measure the levels of severe stress that occur during hull split and harvest (but see below related to barking injury). Both the FloraPulse and Saturas sensors were similar in their ability to measure across a range of SWP that can be expected in commercial almond orchards. Both exhibited some delay (1-2 days) in response to irrigation, but is not clear whether this will represent a serious limitation to their use. The numerical range of both was substantially less than the pressure chamber, particularly for the FloraPulse sensor. For instance, for a range of about 16 bars in SWP, the range exhibited by the Saturas sensor was 8 bars and by the FloraPulse sensor was 4 bars (Fig. 9). Hence irrigation guidelines based on SWP may need to be revised for use with these sensors. Note however, that the uncertainty ranges in Table 2 are based on uncertainty in the sensor reading at a given pressure chamber measured SWP. Hence, because the range of each sensor is substantially less (50 – 75% less) than the range of pressure chamber measured SWP, the uncertainty would be more (2X – 4X) when expressed on an equivalent basis as pressure chamber SWP. That is, the equivalent pressure chamber uncertainty level would be ±8.4 bars for FloraPulse and ±6 bars for Saturas.

An additional feature of the Phytech dendrometers that may be of particular importance in almonds is that the dendrometer also measures the radial growth rate of the trunk. It is reasonable to propose that the bark of trees showing a high rate of radial growth will be more susceptible to shaker damage than trees showing little or no growth, and an experiment was performed to test this hypothesis. Dendrometer readings showed typical patterns of shrink/swell every day, with a steady rate of daily growth up to mid-July, when deficit irrigation for hull split was applied in all trees (Fig. 10). During the deficit period (July 10 – 25), trunks showed shrink/swell patterns typical of water stress, but there was little to no net growth during this period (Fig. 10). After normal irrigation was resumed (July 26), control trunks showed less midday shrinkage, but did not show any net growth through harvest (Fig. 10). These same patterns were also shown by the additional irrigation trees, but soon after the additional irrigations started (July 31), the trunks showed a clear increase in daily growth, which continued until the date of shaking (August 14, Fig. 10). The SWP of all trees was measured on August 13 when the baseline SWP was -8 bars, and on this date the average SWP of all the additional irrigation trees was wetter than the baseline (-6.6 bars) whereas the average SWP of all the control trees was substantially drier than the baseline (-18.1 bars, Table 3). None of the control trees were damaged by the shaker, but 6 of the 9 additional irrigated trees showed some damage, with 3 showing severe damage (Table 3 and Fig. 11). There was some variation in SWP within each group, and on average there was a trend of wetter trees showing more damage than drier trees in the additional irrigation treatment (Table 3). An example non-damaged and severely damaged tree is shown in figure 11. Some of these trees were wrapped with saran to determine if this promoted healing and reduced infection by Ceratocystis, but this will be evaluated in the spring of 2021. It is clear that a high level of water availability promotes trunk growth, and that this can increase susceptibility to barking injury, but further research will be needed to determine if a threshold growth rate can be established as a guideline for shaking. It is noteworthy that overall trunk growth was stopped for the controls during hull split, and despite irrigations after that, trunk growth did not resume. The additional irrigations did cause trunk growth to resume however, so the rate of trunk growth is clearly subject to management through irrigation.

C. Outreach Activities

In addition to presentations at the annual almond industry meetings, I am regularly asked to present to grower meetings by farm advisors.

D. Materials and Methods

All measurements were performed in a 3.5 acre, 13’ x 21’ offset planted Nonpareil (50%), Wood colony (25%), Monterey (25%) orchard, planted on February 3, 2015 at the Kearney agricultural experimental station in Parlier, CA. Trees were headed at planting but not pruned further except to remove lower branches that would interfere with harvest. The 13’ (actually, 4m) tree spacing was determined by the dimensions of the lysimeter (4m long, 2m wide, 2m deep), because the within row distance measured by the lysimeter must match the within row distance occupied by the tree. Irrigation was provided by a single line drip system with one 2 gph (8 lph) dripper per tree starting in year 1, and was gradually increased as the trees grew to a double line drip system with 7 drippers per tree for the Nonpareils and 5 drippers per tree for the pollinizers, in order to favor the development of the Nonpareil. The lysimeter is irrigated by the same system as the rest of the orchard, in order to maintain as much uniformity as possible between the lysimeter tree and the rest of the Nonpareil trees in the orchard. Irrigation was manually managed by the PI, based on periodic SWP measurements, tree growth, the progress of K_c, and the weight of the lysimeter itself (as a relative measure of soil water content). Irrigation for the

Nonpareil rows (every other row) and the pollinizer rows was controlled independently, although for most of the season the entire orchard was irrigated on the same schedule. Cultural practices (other than pruning and irrigation) were conducted by the experiment station staff, with pest and weed control as needed and fertigation applied in 4 equal portions over the growing season as needed based on tree growth, starting in year 3. The weighing lysimeter itself has been maintained by the PI and calibrated at least annually, with no detectible change in calibration since the start of the experiment. A rain gage also measures any drainage (leaching) from the lysimeter, but significant drainage has only occurred twice (2016/17 due to rains and 2019/20 due to winter irrigations) since the start of the experiment. Lysimeter, irrigation (water meter), and other system data is recorded each 10 minutes by a data logger in the lysimeter underground enclosure, and the data accessed over the internet through a dedicated cell phone modem. Percent shaded area was measured photographically for years 1-2, and by Bruce Lampinen's light bar starting in year 3. A CIMIS station located on the field station is used for all reference (ETO) values as well as for other weather information. The micrometeorological tower for the measurement of ETc is managed by a USDA colleague (Andrew McElrone) and the data analysis is being conducted by a UCD trained atmospheric science postdoc. Drone flights are being performed and analyzed by Alireza Pourreza.

E. Publications that emerged from this work

None to report

F. Literature cited

Johnson SJ, Williams LE, Ayars JE, Trout TJ. 2005. Weighing lysimiters aid study of water relations in tree and vine crops. California Agriculture 59:133-136.

Sammis et al, 2004 Pecan Conference proceedings, Las Cruces, NM: 28-33

Tables and Figures.

Table 1. Yield (kernel pounds per acre), midsummer light interception (PAR) and yield per light interception for 2017 (third leaf) to 2020 (sixth leaf) in Nonpareil, and for 2019 – 2020 for the pollinizer varieties in the lysimeter study. Based on the yields and orchard composition (50% Nonpareil, 25% Monterey, 25% Wood colony) the total orchard yield in 2020 was 2,930 kernel pounds per acre.

Variety	Year	Yield (Lbs/acre)	PAR (%)	Yield/PAR
Nonpareil	2017	780	47	17
	2018	1400	55	26
	2019	2070	64	33
	2020	3160	70	45
Monterey	2019	2250	57	39
	2020	2530	68	37
Wood colony	2019	1500	45	33
	2020	2830	58	48

Table 2. Correlation analysis between pressure chamber measured SWP and alternative automated measures of water stress. Uncertainty values correspond to the average range of uncertainty in the sensor value at a given value of pressure chamber measured SWP.

Sensor/ method	Correlation statistics with pressure chamber measured SWP					
	Period A (N=8)		Period B (N=6)		May – Oct. (N=34 to 39)	
	r-square	Uncertainty	r-square	Uncertainty	r-square	Uncertainty
FloraPulse	0.19 (NS)	±1.8 bar	0.86**	±0.6 bar	0.34***	±2.1 bar
Saturas	0.10 (NS)	±3.7 bar	0.90**	±1.0 bar	0.23**	±3.0 bar
Phytech	0.66*	±24 units	0.12 (NS)	±16 units	0.43***	±23 units

Table 3. SWP and bark damage severity for control and additional irrigation trees. Also shown is the range of SWP values observed for control trees that were not damaged (all controls), and for groups of trees in the additional irrigation treatment that exhibited no, some, or severe damage. "Some" damage was defined as wet spots on the bark, but no clear separation between bark and wood.

Treatment and treatment average SWP±SD on August 13 (bars)	Range of tree SWP on August 13 (bars)	Level of bark damage on August 14	Number of trees /9
Control (-18.1 ± 1.5)	-15.6 to -20.9	None	9
Additional irrigation (-6.6 ± 1.5)	-6.7 to -9.6	None	3
	-5.2 to -6.9	Some (wet spot)	3
	-5.4 to -6.3	Severe (¼ - ½ circumference)	3

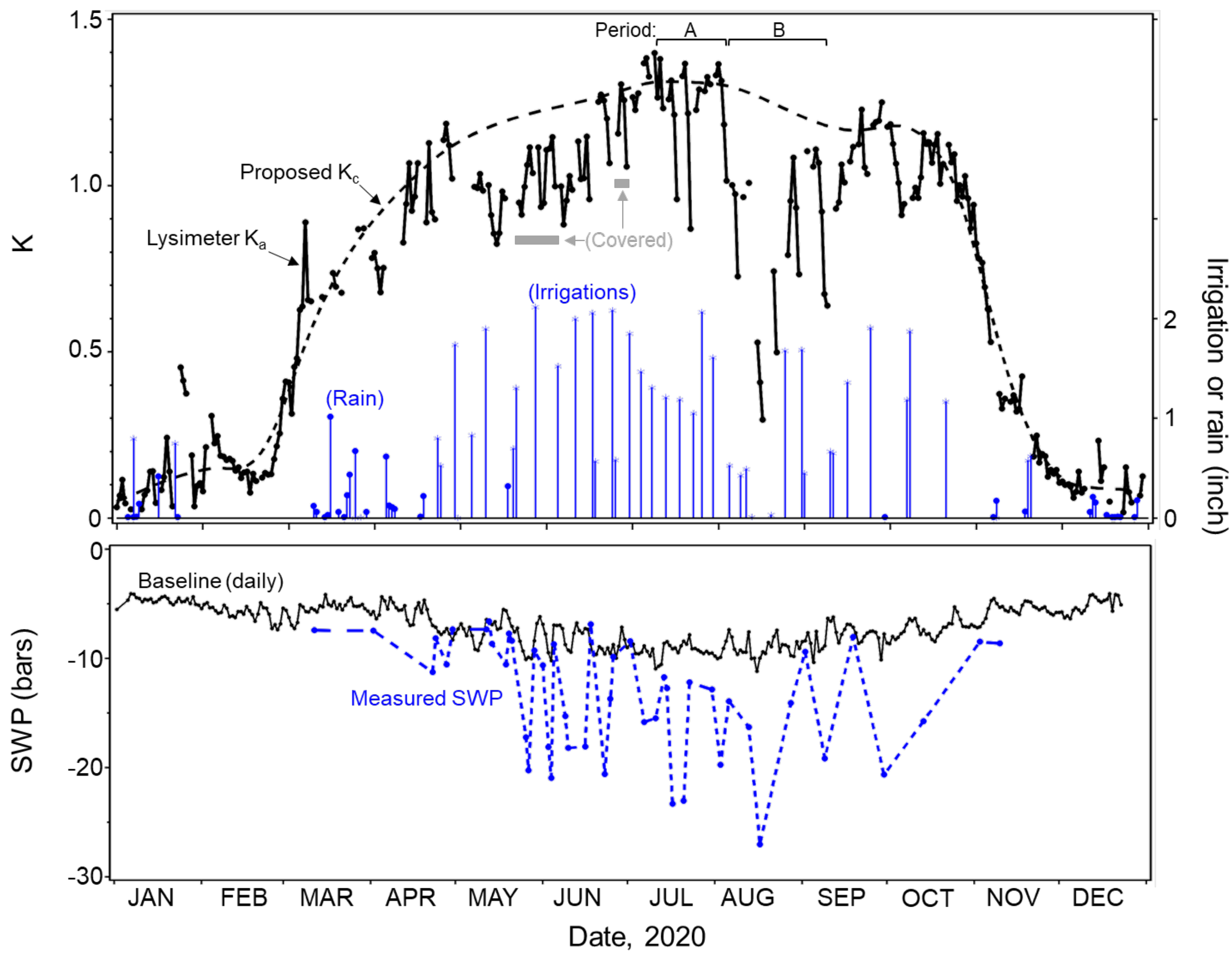


Figure 1. Top panel: daily lysimeter measured (K_a, points connected by solid line, left hand y-axis) and proposed (K_c, dashed line, left hand y-axis) crop coefficients (K) for almonds, as well as daily rainfall and irrigation amounts (right hand y-axis) for 2020. Breaks in the line connecting consecutive K_a points indicate dates when irrigation, rain, or some other disturbance to the lysimeter weight occurred and prevented accurate calculation of K_a. Two specific periods of time (A and B) that were used for a more detailed analysis are indicated, as well as two periods during which the lysimeter surface was covered with a tarp in order to eliminate evaporation form the soil. Bottom panel: daily baseline midday SWP (small dots, solid line) and periodically measured midday SWP (large dots, dashed line) for 2020.

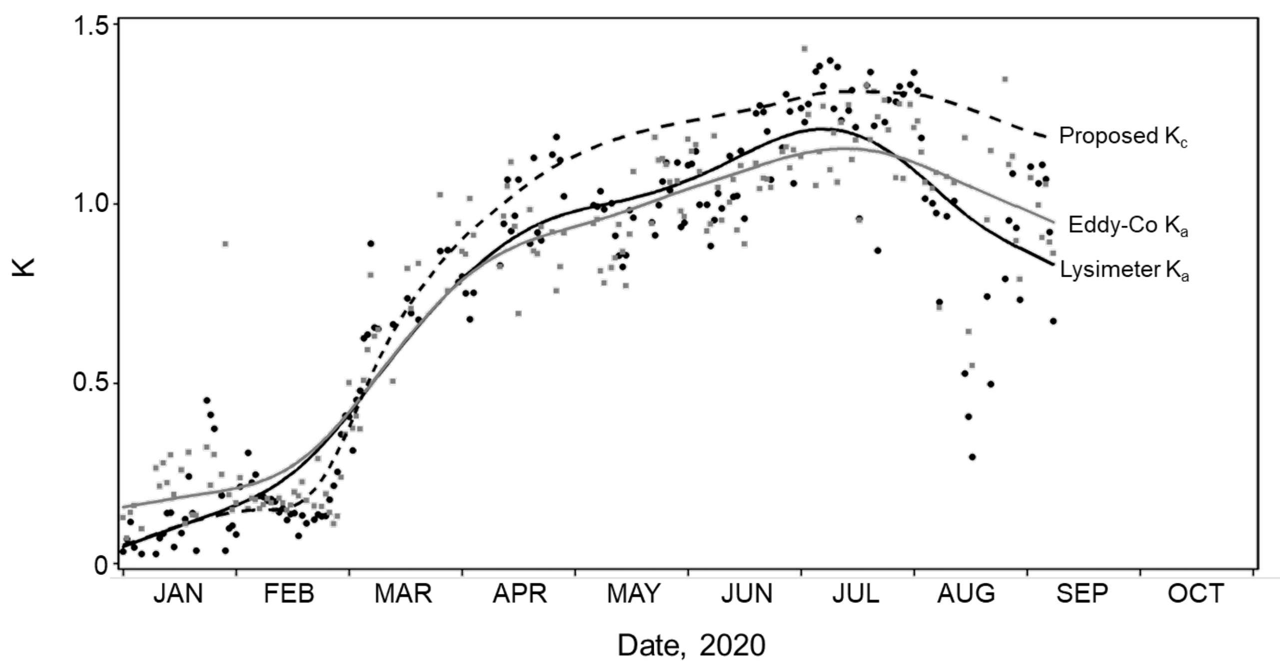


Figure 2. Comparison of the pattern over time for K_a measured by the lysimeter (black dots and solid line) and K_a measured using micro-meterological methods (Eddy-Co, grey squares and solid line), as well as the proposed K_c from Figure 1 (dashed line) for reference. The same set of dates were used for the lysimeter and eddy-co data points, and the splines that smooth variation over time are statistically smoothed to the same degree (50%).

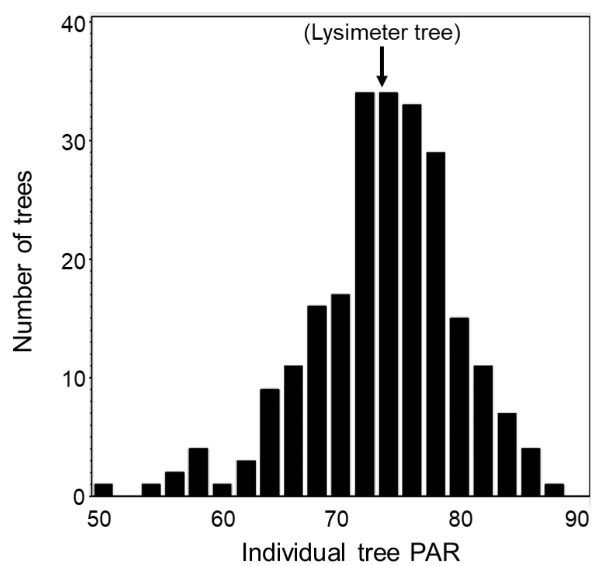


Figure 3. Histogram of the canopy shaded area (PAR) for all nonpareil trees in the lysimeter plot, with the PAR of the lysimeter tree indicated by the downward pointing arrow.

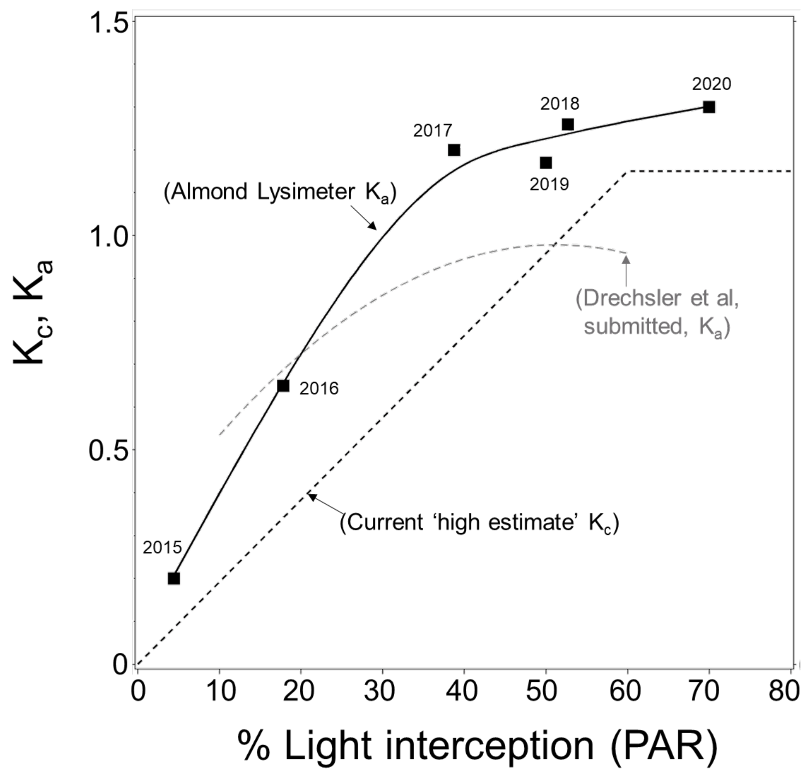


Figure 4. Increase of K_c with increasing canopy size (% light interception) for almond. Shown is the current relation (dashed black line) based on a high estimate of 1.2 for a mature almond orchard, a relation recently found by Drechsler et al (dashed grey line) and the relation found over the first 6 years of the current lysimeter study (black squares and solid line, calendar years indicated adjacent to each point).

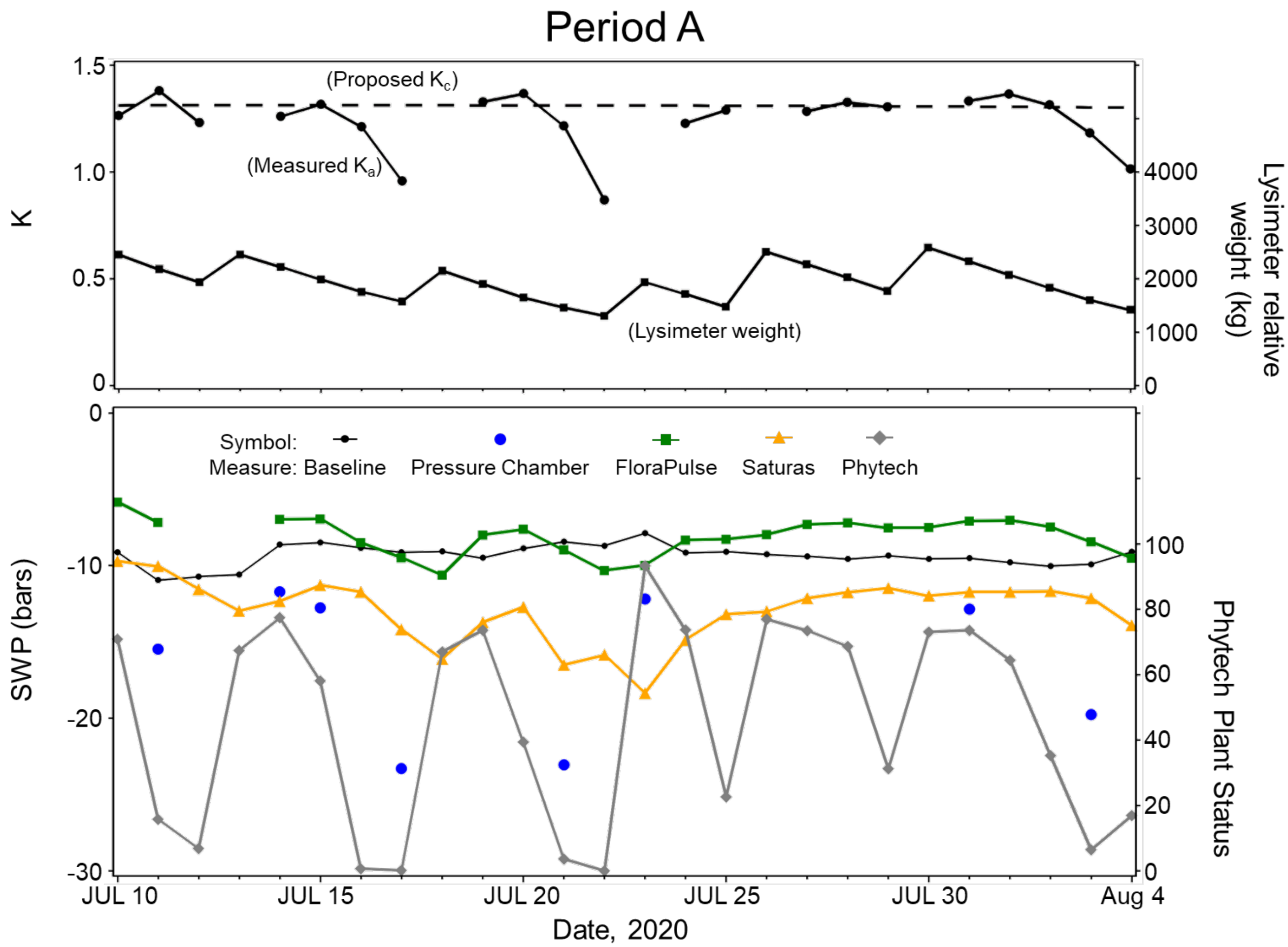


Figure 5. Detail of the hull split deficit irrigation period (period A in Fig. 1). Top panel: K_c and K_a (left hand y-axis), and daily average lysimeter relative weight (right hand y-axis). Bottom panel (left hand y-axis): periodic SWP measured manually with the pressure chamber (large solitary dots), daily baseline SWP (small dots, solid line), and daily SWP measured using the FloraPulse microtensiometer (filled squares) or the Saturas sensor (filled triangles). Bottom panel (right hand y-axis): Daily value of plant status measured by the Phytech dendrometer (filled diamonds). Pressure chamber values are means of 2-6 trees, FloraPulse and Saturas values are means of 2 trees, and Phytech values are means of 9 trees.

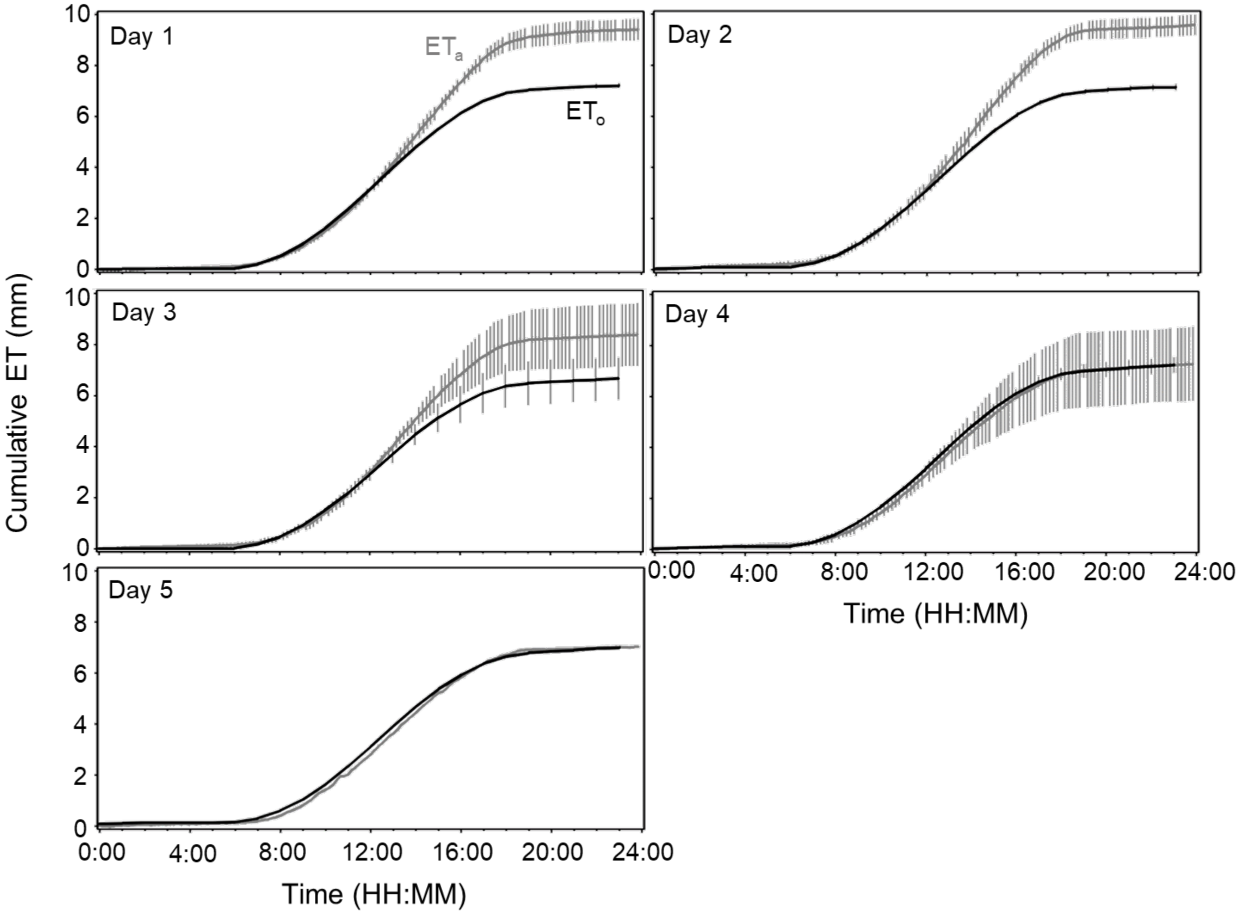


Figure 6. Daily cumulative tree ET_a and reference crop ET_o for increasing time (days) after an irrigation. Each line is the average of 3 irrigation cycles (Fig. 5, July 13-17, 18-22, and July 30-August 4), except for day 5, which is a single day (August 4). Error bars (none for day 5) are ±1 SD and are hidden when smaller than the line thickness. ET_o values are hourly averages, ET_a values are 10-minute averages, and error bars in ET_a have been omitted when at the same time as ET_o.

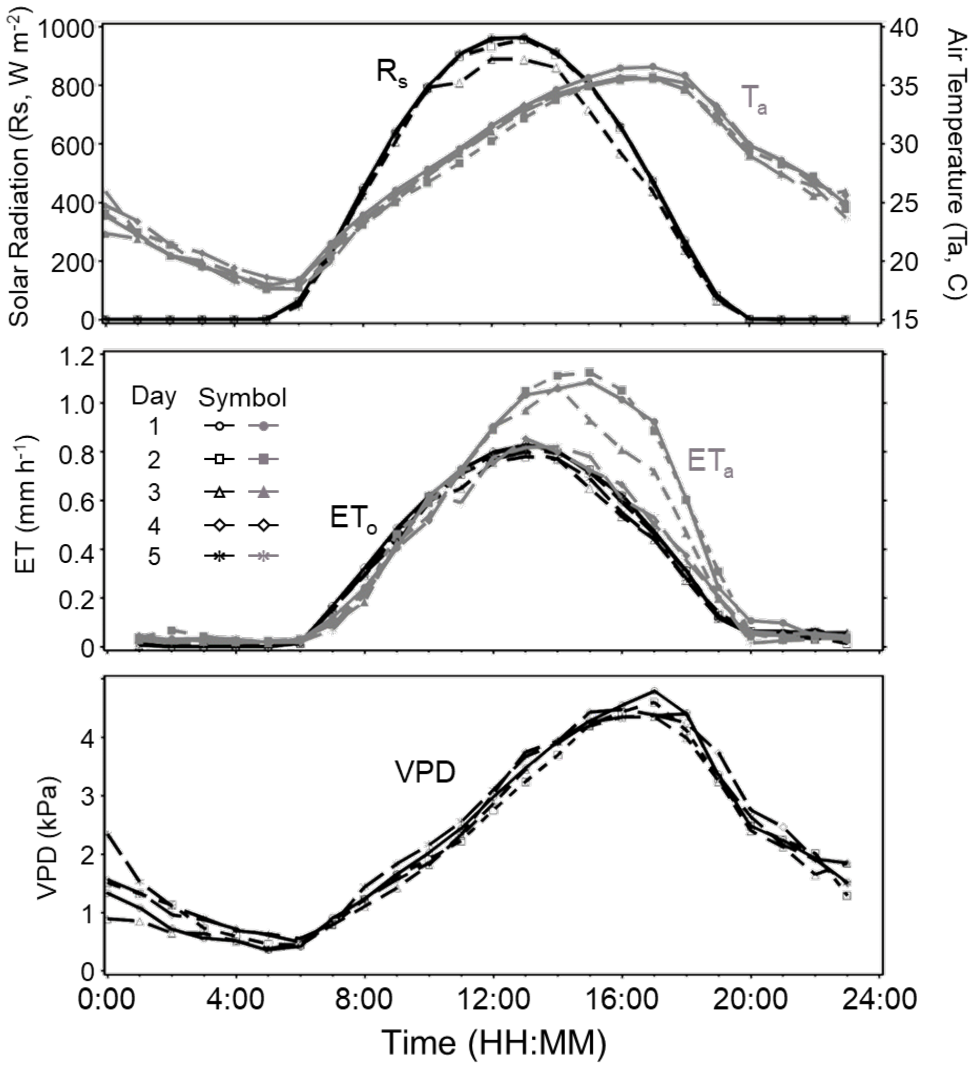


Figure 7. Average daily patterns in hourly values of (top panel): solar radiation rate (R_s) and average air temperature (Ta); (middle panel): rates of reference (ET_o) and lysimeter (ET_a) evapotranspiration; and (lower panel): average air vapor pressure deficit (VPD), for the same set of days as shown in figure 6. The rates of ET_a are based on hourly average values, rather than 10 minute average values (Fig. 6) in order to be consistent with the weather data.

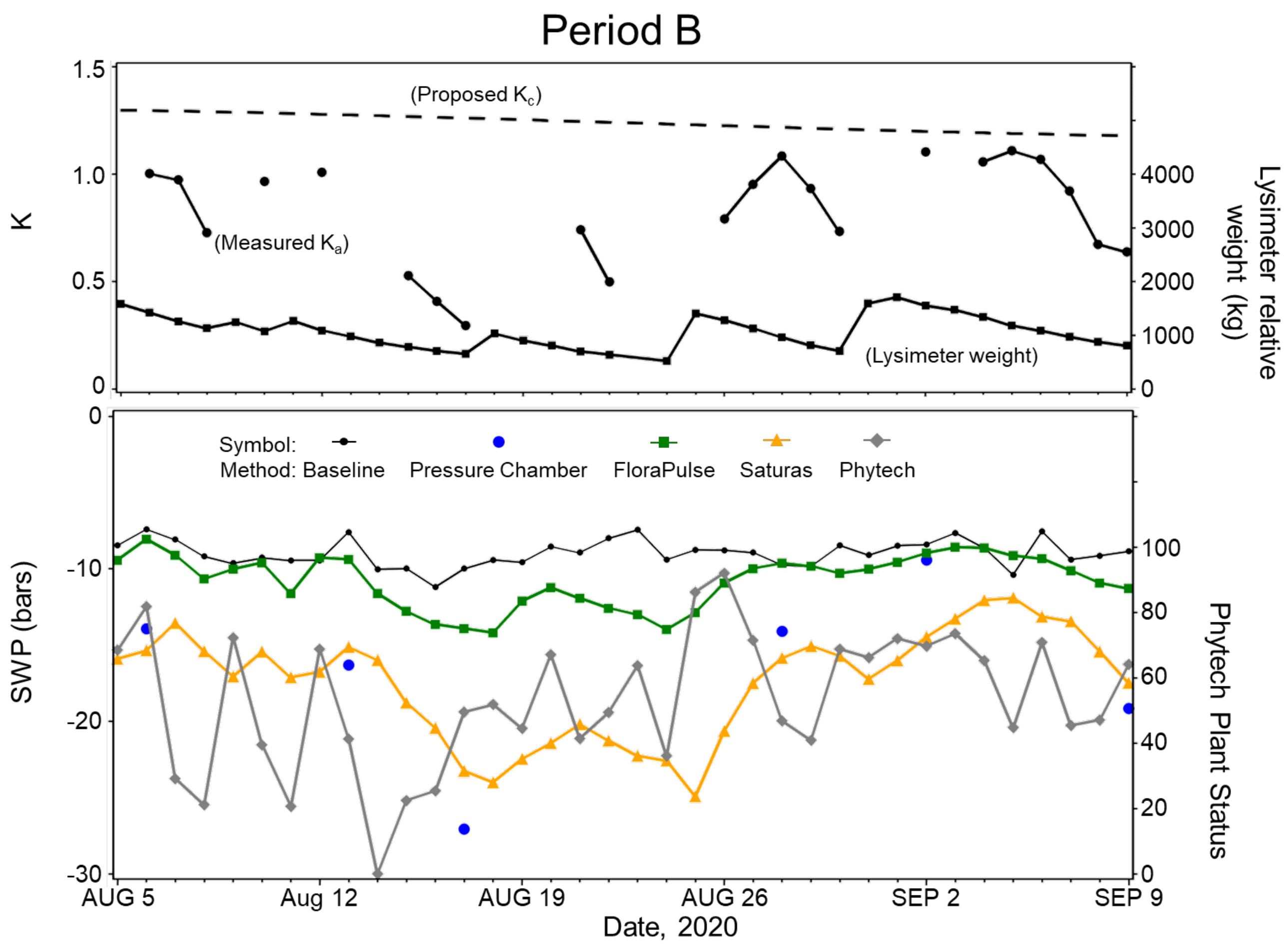
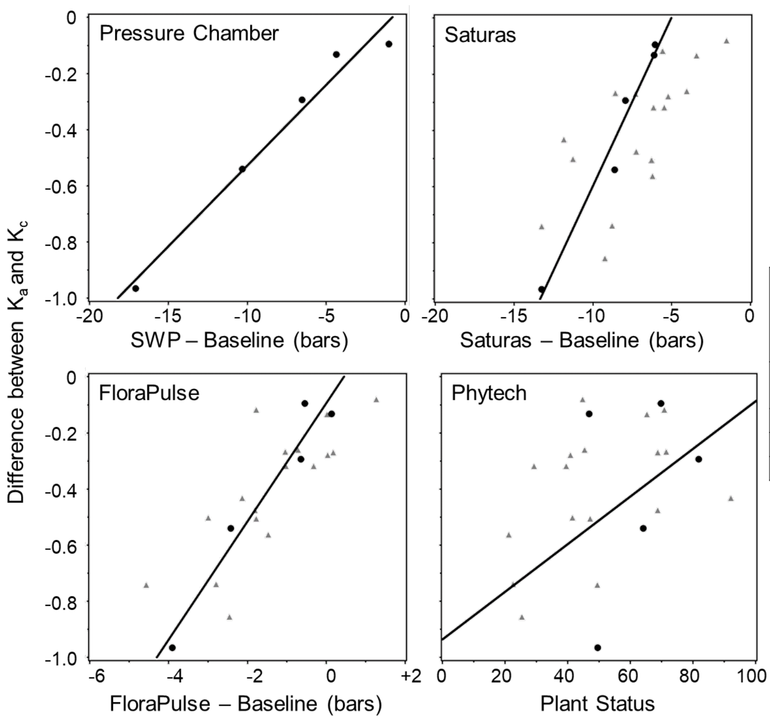


Figure 8. Detail of the harvest deficit irrigation period (period B in Fig. 1), as in Fig. 5. Top panel: K_c and K_a (left hand y-axis), and daily average lysimeter relative weight (right hand y-axis). Bottom panel (left hand y-axis): periodic SWP measured manually with the pressure chamber (large solitary dots), daily baseline SWP (small dots, solid line), and daily SWP measured using the FloraPulse microtensiometer (filled squares) or the Saturas sensor (filled triangles). Bottom panel (right hand y-axis): Daily value of plant status measured by the Phytech dendrometer (filled diamonds). Pressure chamber values are means of 2-6 trees, FloraPulse and Saturas values are means of 2 trees, and Phytech values are means of 9 trees.



Sensor/ method	Correlation statistics with (K_a – K_c)			
	SWP dates (N=5)		All available dates (N=22)	
	r-square	Uncertainty (Kc units)	r-square	Uncertainty (Kc units)
Pressure Chamber	0.97**	±0.07		
FloraPulse	0.95**	±0.10	0.70***	±0.14
Saturas	0.97**	±0.07	0.56***	±0.17
Phytech	0.12 (NS)	±0.39	0.15 (NS)	±0.24

Figure 9. Reductions in K_a associated with reductions in SWP (graphs) and statistical analyses of these relations (inset table) during period B (Fig. 1). Reduction in K_a is reduction form the proposed K_c, and similarly, reduction in SWP for the pressure chamber, Saturas, and FloraPulse sensor is reduction from Baseline SWP. The scale for Phytech is already expressed as a reduction relative to a non-stressed condition. Black points and solid lines in all graphs are data collected on the same dates as pressure chamber measurements (see Fig. 8) and the statistics corresponding to these dates are in the columns below "SWP dates" in the inset table. Gray triangles are data collected on all dates during period B, and the statistics for these combined data are in the columns below "All available dates" in the inset table.

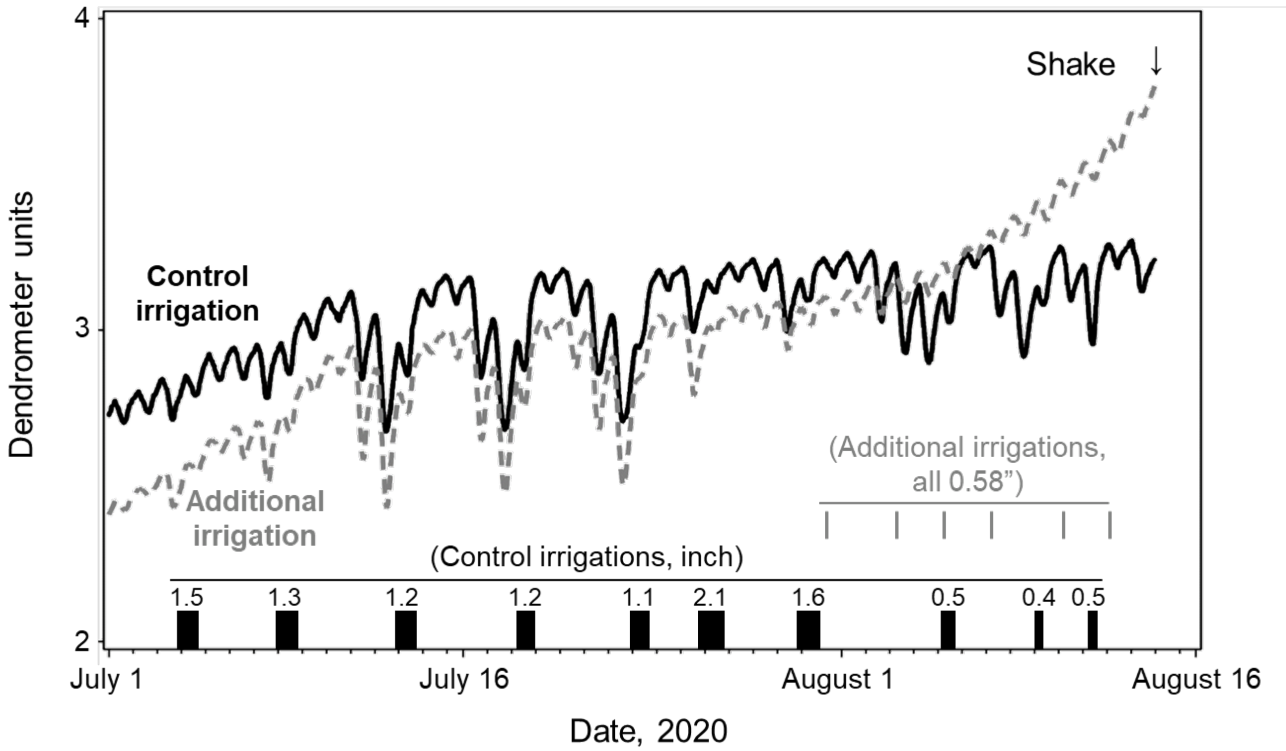


Figure 10. Phytech dendrometer readings (each y-axis unit is approximately 1 mm in distance) from July 1 to shaking (August 14) in the control irrigated trees (solid black line) and additional irrigation trees (dashed grey line). Also shown are the amounts and timings of irrigations in both treatments.

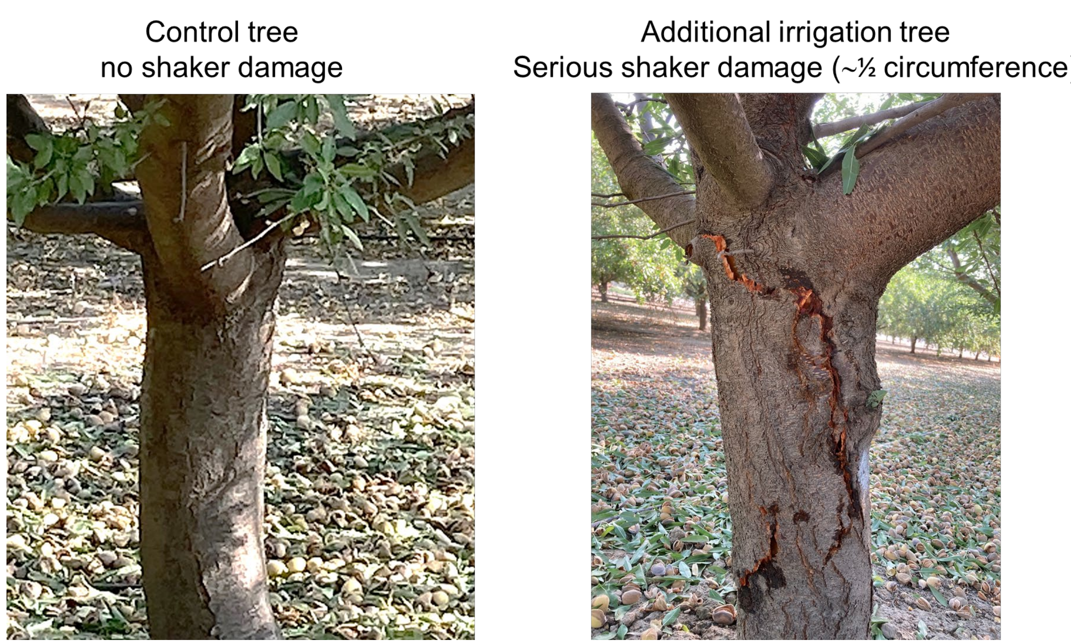


Figure 11. Illustration of a typical non-damaged tree in the control treatment (left) and a severely damaged tree in the additional irrigation treatment.