Almond Water Production Function

Project No.: **15-HORT17-Shackel**

Project Leader: Ken Shackel
Department of Plant Sciences
UC Davis
One Shields Ave.
Davis, CA, 95616
530.752.0928
530.752.0122 (Fax)
kashackel@ucdavis.edu

Project Cooperators and Personnel:
David Doll, UCCE – Merced County
Bruce Lampinen, UC Davis
Allan Fulton, UCCE – Tehama County
Blake Sanden, UCCE – Kern County

Objective:

Develop a water production function (WPF) for almonds grown in California that will relate potential yield to water applied, accounting for the site-specific effects of orchard cover, soils, varieties, and physiological level of stress experienced by the tree.

Interpretive Summary:

The 2015 season was the third year of imposing irrigation regimes over a fairly wide range of 70 -110% ET (about 22” to 43” applied water, March 1 - September 1) in Kern, Merced, and Tehama Counties, representing a range of environments and soil conditions. At all sites, reduced irrigation was always associated with significantly more water stress (more negative SWP), with monthly average values ranging from -9 bar (close to baseline, no stress) to slightly below -20 bar (moderate/severe stress), depending on the site and treatment. Nonpareil yields in the 100% ET treatment have varied between about 1,700 and 3,300 kernel pounds per acre, depending on the year and site. Yield at the Tehama site has been the most stable (about 2,100 kernel pounds/acre), but has also shown the least response to irrigation. A trend analysis using all data (2012-2015) was performed to account for both pre-treatment differences in yield as well as yearly variations in yield, in order to determine which factors which may determine yield are responding to irrigation over time. Taken together, all sites are exhibiting a trend over time of small but statistically significant increases in kernel weight and %PAR with increased irrigation, but even after three years of imposing irrigation treatments, the increases in these factors have not translated into yield differences that are large enough to give clear statistical separation between irrigation treatments across all sites. It is possible that the same water production function may not apply to all orchards across the state, or alternatively, that some orchards may require a relatively long time for yields to show the effects of water management. Based on the trends over time, as well as the 2015 yield results for the two sites that have shown meaningful differences in yield between the highest and lowest irrigation treatments (Kern and Merced), our current best estimate for the range of

irrigation that we applied is an increase of about 40 kernel pounds per acre per inch of applied water.

Materials and Methods:

A randomized complete block experiment was set up in commercial almond orchards in three counties (Tehama, Merced, and Kern). At each site, 4 to 5 irrigation treatments, with target levels ranging from 70% - 110% ETc, in 3 to 6 blocks (**Table 1**) were established by modifying the existing irrigation system. Applied irrigation amounts were measured approximately weekly in at least half of the experimental plots using water meters, and periodic measurements of soil water to 9' were made with a neutron probe throughout the season in order to estimate net soil water depletion in each plot. For plots without a water meter or neutron probe data, the treatment averages were used as estimates. Periodic (at least weekly) measurements of midday stem water potential (SWP) were made on individual monitored trees in each plot. Mid-season canopy cover (% PAR Interception) was measured using the light bar technique developed by Bruce Lampinen, and plot yields as well as individual tree yields for SWP monitored trees were obtained. These data were used to calculate yield per unit PAR intercepted. At the Kern site, additional treatments were imposed as well as more detailed measurements made of ET and canopy imaging. These results will be presented at the end of this report.

Table 1. Numbers of blocks and target levels of irrigation treatments at each location of the study.

Location	# of blocks	Treatment targets (% ET)
Kern	6	70, 80, 90, 100, 110
Merced	3	70, 80, 90, 100, 110
Tehama	6	74, 86, 100, 116

Results and Discussion:

Irrigation Amounts, Soil Moisture, and ET. This is the third year of applying different amounts of water, approximating 70 – 110 % ET, in a randomized complete block design at three orchard sites across the state. One important irrigation decision is when to begin irrigation and how much to apply in the spring, and when comparing applied water to tree water demand (ETc, as calculated based on orchard specific bloom dates and real time reference ET, [CIMIS ETo]), there have been substantial differences from site-to-site in some years. In all years, irrigation at the Kern site has started earlier and kept ahead of demand compared to the other sites, and this was also the case in 2015, with the 100% treatment staying slightly ahead of calculated demand through July (**Figure 1**). This is due to a generally lower rainfall at this site, a corresponding effort to control salinity and the reality of a more rapid depletion of stored soil moisture through August compared to the other sites (**Figure 1**). In 2015 the Tehama and Merced sites started somewhat later but closely matched calculated ETc for the highest irrigation treatments (**Figure 1**). Irrigation treatments at all sites applied significantly different amounts of water seasonally (**Table 2**), but there were important differences between sites in the quantity of soil water used by the trees, with the Merced site generally showing the highest use of soil water and the Tehama site showing the least (**Table 2**), similar to 2014 results. As was the case in 2014, the Merced site showed the highest average soil water content and the Tehama site the lowest, with Kern intermediate (**Figure 1, right panel**). Presumably, these differences in average soil water content and the use of stored soil water reflected site difference in soil texture and water holding capacity. However, it was surprising to note that only the Tehama site showed a statistically significant difference in the use of soil water due to irrigation treatment (**Table 2**), with less irrigation giving correspondingly more use of soil moisture. At all sites the highest soil water use was associated with the lowest applied irrigation amounts, but other than the Tehama site there was little evidence that a progressive reduction in applied water would lead to a progressive increase soil water uptake, as might be expected. When the contribution of soil water was included as part of the irrigation treatment (expressed as actual % of ET, **Table 2**), the separation between treatments was typically not as large as was planned, and in some cases the order of adjacent treatments was reversed (**Table 2**), but on average, the range in water use across all sites was about 30% of ET, compared to the designed 40%.

Table 2. Treatment mean values and statistical comparison (means followed by different letters are significantly different at P<0.05) for applied water, soil water depletion and water balance estimates of % full ET for each location for the period March 1 – September 1, 2015. Soil water depletion for the Tehama site was February 10 – September 1, 2015.

Location (estimated ET_c)	Treatment	Applied water (")	Soil water used (")	Actual %ET_c
Kern (43.4")	110	43.4a	5.5	112a
	100	41.3a	4.0	104ab
	90	35.7b	7.2	99abc
	80	32.1bc	6.6	89bc
	70	26.8c	7.5	79c
Merced (41.6")	110	42.8a	5.5	116a
	100	41.0a	7.5	117a
	90	35.0b	9.3	107ab
	80	30.6b	8.5	94b
	70	30.3b	10.9	99b
Tehama (40.5")	116	39.1a	2.2b	102a
	100	32.8ab	3.2ab	89ab
	86	27.2bc	3.6ab	76bc
	74	24.7c	4.5a	72c

Plant Response (SWP and PAR). As in previous years, at each site there was a close relation of SWP to applied water, with less applied water resulting in lower (more stressed) SWP values (**Figure 2**) and a clear statistical ranking in treatment order for the seasonal average SWP (**Table 3**). However, the Kern site, in which the water applied to both the 100 and 110%ET treatments was general higher than the calculated %ET (**Figure 1**), exhibited a~~n~~

SWP which was generally lower than the SWP in the same treatments in Merced, which were at or below the calculated %ET (**Figure 1**). The more negative SWP and more rapid early season depletion of stored soil water in Kern may indicate that the net almond ET at the Kern site was running above our "calculated Kc * ETo" based values, and that adjustments to increase irrigation were still insufficient to maintain baseline SWP values in the 100 and 110% treatments. Tehama generally exhibited the most negative SWP values (**Figure 2**, **Table 3**), even though the irrigation compared to ET at this site was similar to the other sites (**Figure 1**). At the Merced site, the SWP values were all in a minimal to very mild stress range for most of the season, compared to a range of mild to moderate/severe stress in Tehama and Kern. In this third year of treatments, percent PAR showed statistically significant differences due to irrigation at all sites, decreasing with less irrigation and with a ranking that was generally consistent with the irrigation treatment (**Table 3**). In the first year there was no statistical effect on PAR and in the second year only the Kern site showed this effect, so this trend of significant differences developing over time is a clear indication that irrigation is having a long term effect on these almond orchard canopies.

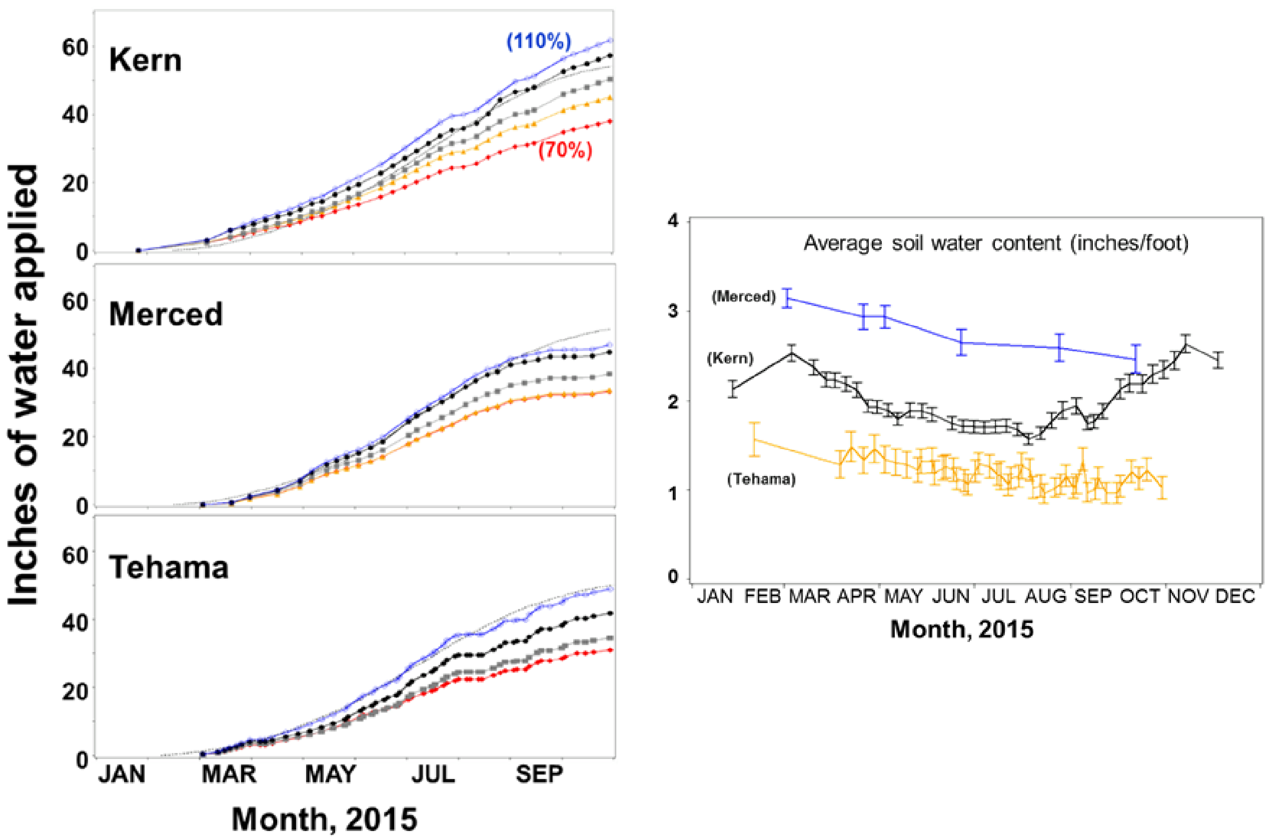

Figure 1. Seasonal pattern of cumulative applied irrigation amounts (left panel) and average soil water content (1' – 9' depth, right panel) at each of the three WPF sites in 2015. For reference, the dashed lines in each graph of the left panel are the calculated ETc for almond using the most accurate estimates available for local, real time reference ET (spatial CIMIS ETo) and almond crop coefficients (Kc). In essentially all cases, the cumulative applied irrigation ranked in treatment order, from the lowest (70% ET) to the highest (110% ET) irrigation treatment level. Soil water content is averaged over all treatments, only to illustrate the overall seasonal pattern and differences between sites.

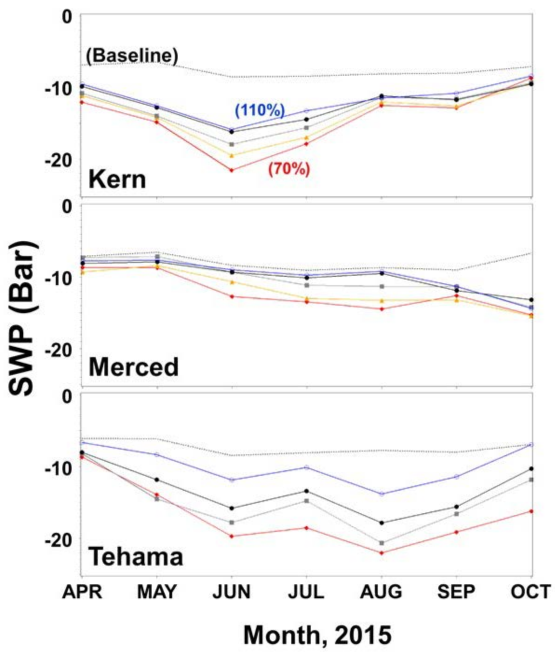

Figure 2. Seasonal pattern of monthly average stem water potential (SWP) for each treatment at each location, with the highest and lowest irrigation treatments indicated for Kern (other sites were also consistent with the irrigation treatments). Also shown for reference is the fully irrigated (non-stressed) baseline SWP (black dashed line).

Table 3. Average (mean) seasonal tree SWP (April - September), percent light interception (PAR), kernel weight, and yield for the different sites and irrigation treatments (70 – 110 %ET) in 2015. Means followed by the same letter are not significantly different. An absence of letters also indicates that there was no significant treatment effect.

Site	Treatment	SWP (Apr-Sep)	PAR (%)	Kernel weight (g)	Kernel Yield (#/ac)	Kernel Yield (#/PAR)
Kern	110	-12a	76a	1.04ab	2,770a	36.7a
	100	-13ab	75ab	1.08a	2,410b	32.1b
	90	-14abc	73abc	1.03b	2,350b	32.2b
	80	-14bc	72bc	1.02b	2,370b	32.7b
	70	-15c	72c	0.92c	2,140b	29.8b
Merced	110	-9a	70.5a	1.23	2,220	31.3
	100	-9a	70.2a	1.17	2,410	33.9
	90	-10ab	65.8ab	1.22	2,080	31.5
	80	-11bc	63.9b	1.19	1,820	28.3
	70	-12c	64.2b	1.14	1,750	27.2
Tehama	116	-11a	71.2a	1.23a	2,440	34.4
	100	-14b	66.1b	1.16ab	2,230	33.9
	86	-16bc	66.3b	1.11bc	2,380	36.0
	74	-18c	65.5b	1.05c	2,170	33.0

Plant Response (Kernel Weight and Yield). Consistent with the pattern of significant irrigation differences developing slowly over time that was shown in PAR, the influence of irrigation on kernel weight, which was only significant at the Kern site in 2014, was significant at both Kern and Tehama in 2015, with a clear treatment ranking showing that decreased kernel weight was associated with decreased irrigation, as expected (**Table 3**). Irrigation only significantly influenced yield at the Kern site, although the ranking of yield in the other sites were also consistent with the expected association between lower yields and lower amounts of irrigation (**Table 3**). Yield per unit PAR (#/PAR. **Table 3**) was always numerically lowest for the lowest level of irrigation at all sites, and was significantly higher in the highest irrigation treatment at the Kern site, but this was not the case for the other sites.

Yield Over time and the Response to Irrigation. Average yields have shown substantial variation at Kern and to some extent Merced over time since before the imposition of irrigation treatments in 2012, but have been relatively stable in Tehama (**Figure 3**). In addition, despite the use of a randomized complete block design, plot average yields were not identical prior to treatment imposition, particularly at the Kern site, where the plots representing the highest irrigation treatments (100% and 110%) had somewhat higher initial yields than the plots representing the lowest irrigation treatment (70%, **Figure 3**). One of the primary objectives of this research is to describe the relation of applied water to yield, but for the three years of treatment imposition, there has been no clear response of yield to applied water at Tehama and Merced (**Figure 4**). Also, the apparent positive response of yield to water at Kern is only due to the generally higher yields and higher applied water amounts in 4 of the 5 treatments in 2013 compared to the other years, with no clear relation among the irrigation treatments

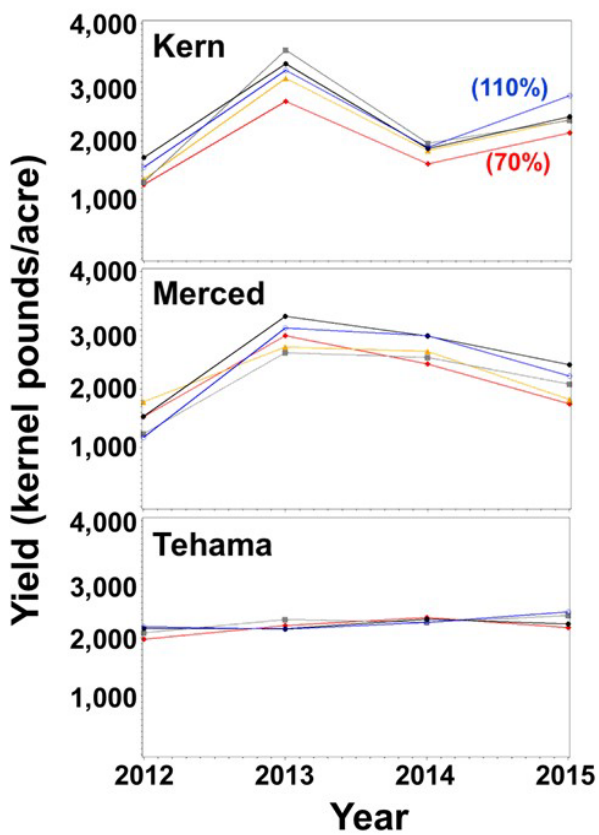

Figure 3. Average yields beginning prior to any irrigation treatment (2012) and for the 3 years of treatment imposition (2013 – 2015). Symbols as in **Figure 1**.

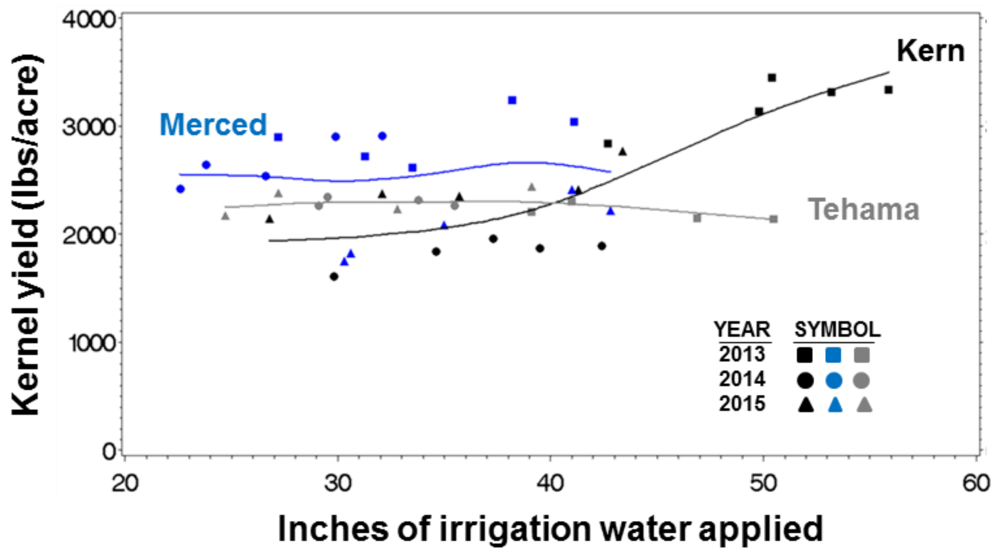

Figure 4. Summary of the response of yield to applied water (March 1 – September 1) over the first 3 years of imposing irrigation treatments at each site, using different symbols to represent years and showing the average trend line at each site for all years.

themselves in 2013 (**Figure 4**). It is surprising, given a range of 30% ET in calculated water use, that we have not seen a stronger response in yield, but in view of the slowly developing statistical effects observed in long term canopy effects (PAR), it is possible that yield effects will follow over time, and hence that a trend analysis will be a more appropriate method to evaluate the sensitivity of yield to applied water.

Yield Trend Analysis. In order to remove the variation caused by yearly changes in overall yield (**Figure 3**) as well field variability (blocks), for each year the difference between the treatment yield and the average yield is calculated on a block basis and graphed over time (**Figure 5**). At the Merced site for example, the 70% ET treatment had about 100 kernel pounds over the average in 2012 (before treatments were started), but had declined to about 300 kernel pounds below the average by 2015 (**Figure 5**). In contrast, the opposite trend can be seen for the yields in the 110% ET treatment (**Figure 5**). For each treatment at each site, and for yield, %PAR, and kernel weight, these trends were expressed as a percent change per year in order to compare all sites on the same basis (**Figure 6**). For yield (**Figure 6, top**), the Merced and Kern site show a positive trend with increasing irrigation, but also substantial variation, and even though the Merced site appears to show the strongest trend (5-10% per year for the highest and lowest irrigation treatments) none of the regression lines shown are statistically significant. More modest but statistically positive trends with increasing irrigation were apparent for all sites in %PAR (**Figure 6 middle**) and kernel weight (**Figure 6 bottom**), although the trends only represented an increase of about 0.05% per year per 1 increase in %ET. Put on a more practical basis, after 3 years of treatments, these trends would only indicate an expected increase in %PAR and kernel weight of about 3%PAR and less than 0.01g, respectively, per inch of irrigation. Even for the Merced site, which showed a clear trend difference in yield between the highest and lowest irrigation treatments (**Figure 5**) the yield difference in 2015 reached about 500 kernel pounds per acre, and was associated with a difference of about 12.5” in applied water, giving a response of about 40 kernel pounds (1.6%, based on an average yield of 2,500 kernel pounds per acre) per inch of water. For the Kern site, the yield difference between the highest and lowest irrigation treatments in 2015 was 630 kernel pounds per acre (**Table 3**), with an applied water difference of 16.6” (**Table 2**), giving a very similar estimate of 37 kernel pounds per inch of water. It should be noted that these estimates are based on the changes in yield that we have seen at the Kern and Merced site within the range of water applications at those sites, hence it should be considered a ‘marginal return’ of yield per inch of water. It would not be appropriate to extrapolate these figures to the total yield per total applied water, even at these sites, because it is not expected that yield will simply be a linear function of applied water without considering the soil water contribution.

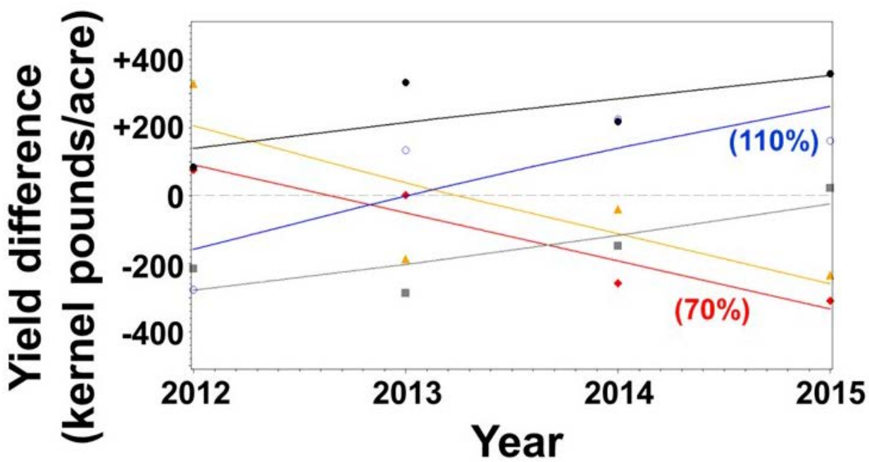

Figure 5. Example of a yield trend analysis using Merced yields. Each point is the difference in yield between the treatment (same symbols as in Fig. 1) and the mean yield for that year. An upward slope indicates a trend of relative increase over time compared to the other treatments, and a downward slope indicates a trend of decrease.

.

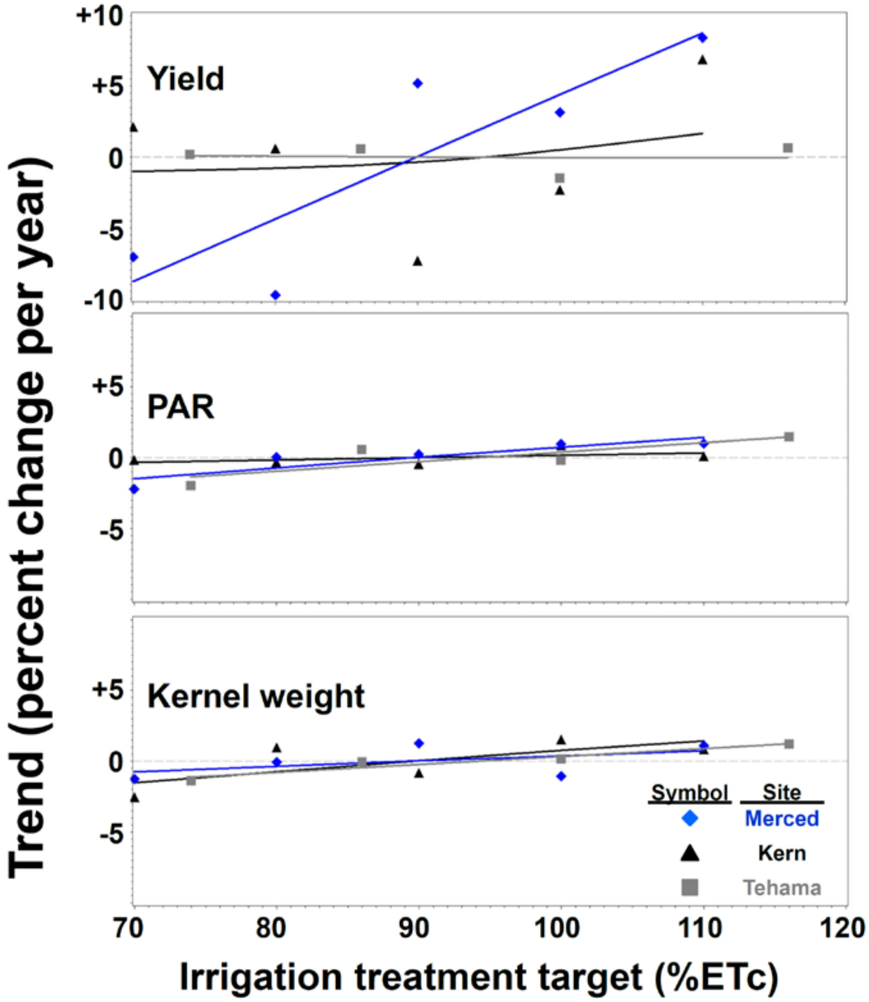

Figure 6. Trend analysis for Yield, PAR, and Kernel weight for the first 4 years of this project. For simplicity, irrigation is expressed as the treatment target value at each site. Lines with a steeper slope indicate for which factors and in which locations more response to irrigation was observed, but it should be noted that the individual lines shown are not statistically significant, but that the overall trend in PAR and kernel weight are significant (see text).

Conclusions:

It is clear that at essentially all sites there have been small but persistent increases over time in all of the factors that should lead to an increase in orchard productivity with increased water applied. However, even after three years of imposing irrigation treatments, the increases in these factors have not translated into yield differences large enough to give clear statistical separation across all sites. The Kern site has typically shown a pattern of earlier statistical separation over time in most factors, compared to the other two sites (Merced and Tehama). This may provide an accurate picture for the almond industry as a whole, since it may be expected that the speed and degree of tree responses to applied water will vary depending on soil and other environmental conditions. It is possible that the same water production function may not apply to all orchards across the state, or alternatively, that some orchards may require a relatively long time for yields to show the effects of changes in water management. Based on the trends over time as well as the 2015 yield results, for the two sites that have shown meaningful differences in yield between the highest and lowest irrigation treatments, our current best estimate for the marginal almond yield response to applied water is about 40 kernel pounds per acre per inch.

Research Effort Recent Publications:

None.

References Cited:

None.

Kern Materials and Methods Using CERES Imagery for Conductance/Water Stress Measurement

The Kern County trial is the largest and most complex of the three statewide project sites. With the cooperation of Paramount Farming Company (now Wonderful), Jain Irrigation, Galcon Controllers, CERES Imaging, Phytech International, Smartfield, Inc., Rainbird and Hortau we have been able to install a double-line drip system powered with a variable frequency drive booster that has independent control of plots that are 6 rows wide by 15 or 16 tree long (**Figure 2**). Thus, differential irrigation amounts are achieved using a uniform flowrate, but varied duration to achieve as close as possible to a 70, 80, 90, Hull Split RDI, 100 and 110% ET application of water.

Objectives:

1) Quantify **kernel yield in lbs/inch actual ET** (applied water + soil moisture depletion – leaching) under non-limiting fertility levels by varying depths of applied irrigation. (Primary objective common to all 3 sites.)

Kern Specific Objectives:

2) Quantify the interaction of hull-split Regulated Deficit Irrigation on the yield function with a simplified 50% ET irrigation application from mid-June to Nonpareil harvest irrigation cutoff – about 6 weeks.
3) Assess the yield benefit of “pulsed” (6 hours on, 6 hours off for 4 cycles over 48 hours) vs. continuous (24-hour set) irrigation.
4) Assess the grower friendliness, benefits and accuracy of in-situ data collection using web-based monitoring of trunk diameter (Phytech dendrometers), infrared sensed canopy temperature (Smartfield) and soil water content (Rainbird Climate Minder capacitance probes, Hortau tensiometers).
5) Assess the accuracy and relationship to kernel yield of remotely sensed aerial imagery used to calculate crop water stress (Conductance measurement, **Figure 2**) and tree biomass/vigor (NDVI, normalized differential vegetative index) using images supplied by CERES Imaging.
6) Assess the feasibility, final water use and yield of high frequency “on-demand” plant stress and soil moisture triggers for irrigation scheduling (Unavailability of extra water due to drought canceled these treatments.)

The following discussion and figures will focus on plot size, applied water, final Kernel yields (the actual Water Production Function) and whole orchard water stress – which was only possible to measure using CERES Conductance imagery (objective 5). This metric is calculated using canopy temperature, vapor pressure deficit and a proprietary algorithm to estimate stomatal conductance as the flow of water vapor from the leaf. **Figure 1** shows the correlation of the average CERES conductance measurements for 9 flyovers from 3/25 to 9/22/2015 with seasonal applied water for 50 metered plots across the trial. You will notice that there is considerable variability of total applied water that does a good job of covering the 70 to 110% range but is not perfectly clumped into our 5 exact percentage treatment groups. This is from leaks (gophers), occasional controller/program errors and flow meter variability.

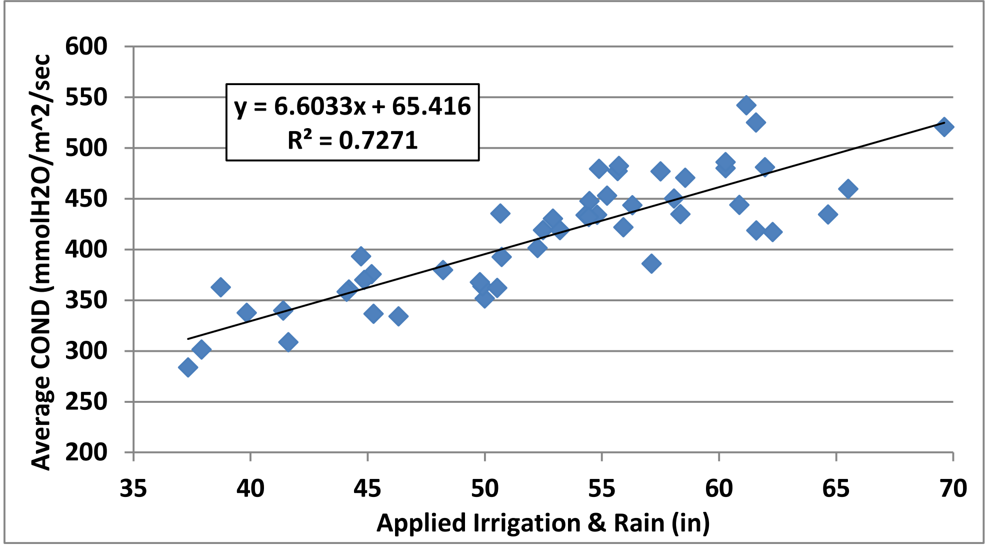

Figure 1. Average CERES conductance water stress (9 flights from 3/25-9/22/2015) as a function of total applied water for 2015.

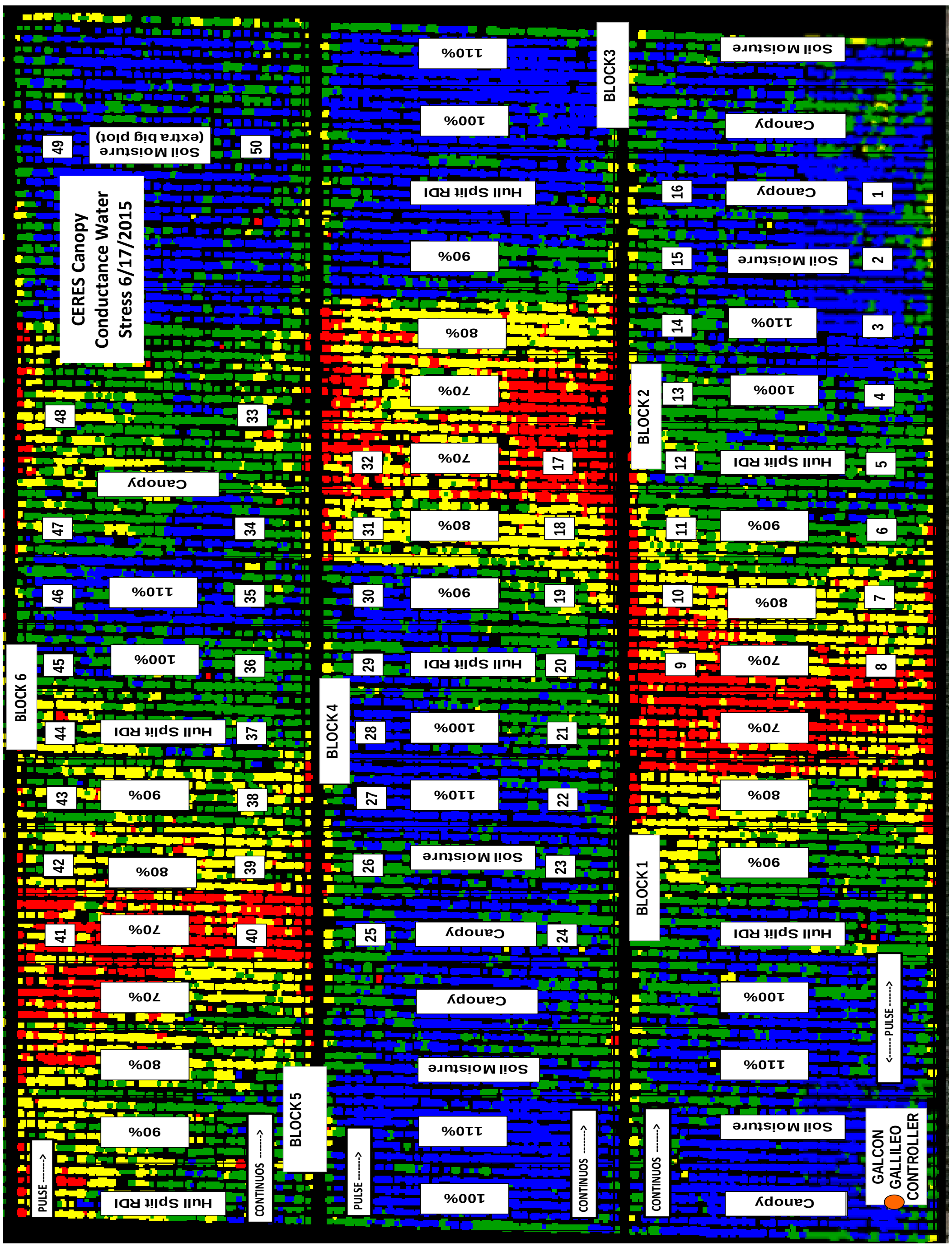

Figure 2. Plot layout with colorized image of from CERES flyover on 6/17/15 revealing stress in deficit irrigation treatments.

A 73% correlation of a plant-based water index with total seasonal applied water is truly excellent. So do the CERES conductance measurements give us a more comprehensive way to examine stress over the whole orchard and see if we have indeed achieved the differential levels of stress designed for this trial? Absolutely! **Figure 3** below shows the **Figure 1** CONDUCTANCE/stress data arranged by irrigation treatment for all 6 replicated metered plots (3 pulse plots, 6 hour pulses for a total of 24 hours in 2 days, and 3 continuous plots - normal 24-hour irrigation sets). There was NO significant yield effect by irrigation method (continuous vs pulse irrigation) for either CONDUCTANCE or kernel yield.

These are great results given the know variability exhibited in measured flow rates shown in **Figure 1.** But the density of this data provides numbers for every tree in the orchard.

Figure 4 shows the relationship of CERES conductance measurements for a single tree stem water potential (SWP) over the 2015 season. R^2 ranged from 0.41 to 0.62 for a given date in 2014. For individual dates in 2015 the R^2 was much less; from 0.03 to 0.29 at best. Taken as a whole, without respect to date, **Figure 4** shows an R^2 of 0.29 for a logarithmic regression. Whether the CERES CONDUCTANCE or SWP is most accurate to explain plant water stress we can't say at this time.

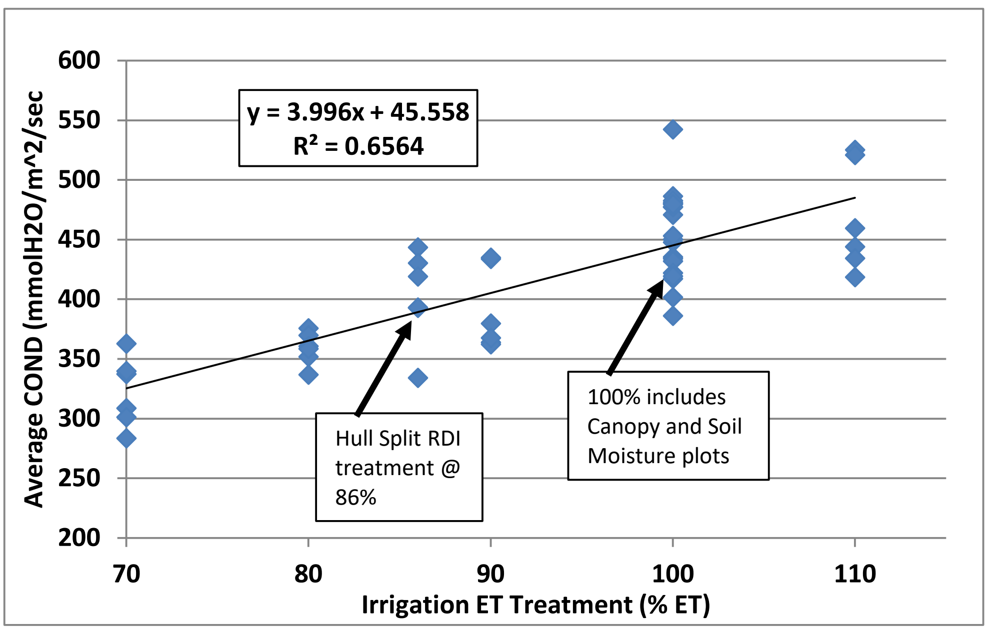

Figure 3. Average plot CONDUCTANCE (3/25-9/22/15) by irrigation treatment.

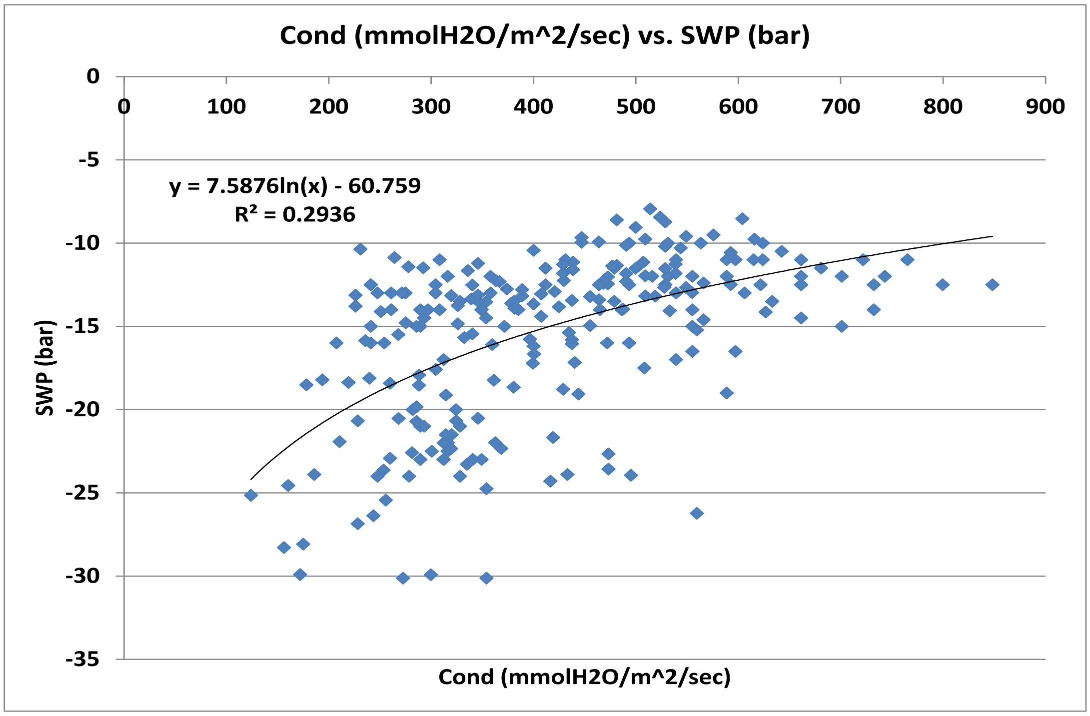

Figure 4. Individual tree Conductance compared to SWP measured the same afternoon for the 2015 season.

Figures 5 A and B illustrate the continuously monitored expansion and diurnal shrink/swell in trunk diameter (wavy line) from 4/24 to 6/7 for one of the 110% and 70% plots. The square peaks indicate the time, duration and depth of water applied by one of the double line hoses. This chart also reveals the problems with remote telemetry in that the 110% water meter ceased working after 5/24. The magnitude of the axes is identical; revealing that the 70% irrigation tree had a nearly equal increase in growth from bloom to mid-May as did the 110% irrigation tree. But after this period you will notice some continued erratic growth in the 110% tree while the growth in the 70% plateaus and maximum daily shrink/swell (MDS) oscillation in the 70% tree increases dramatically – as much as 250-300 microns/day, indicating significant water stress.

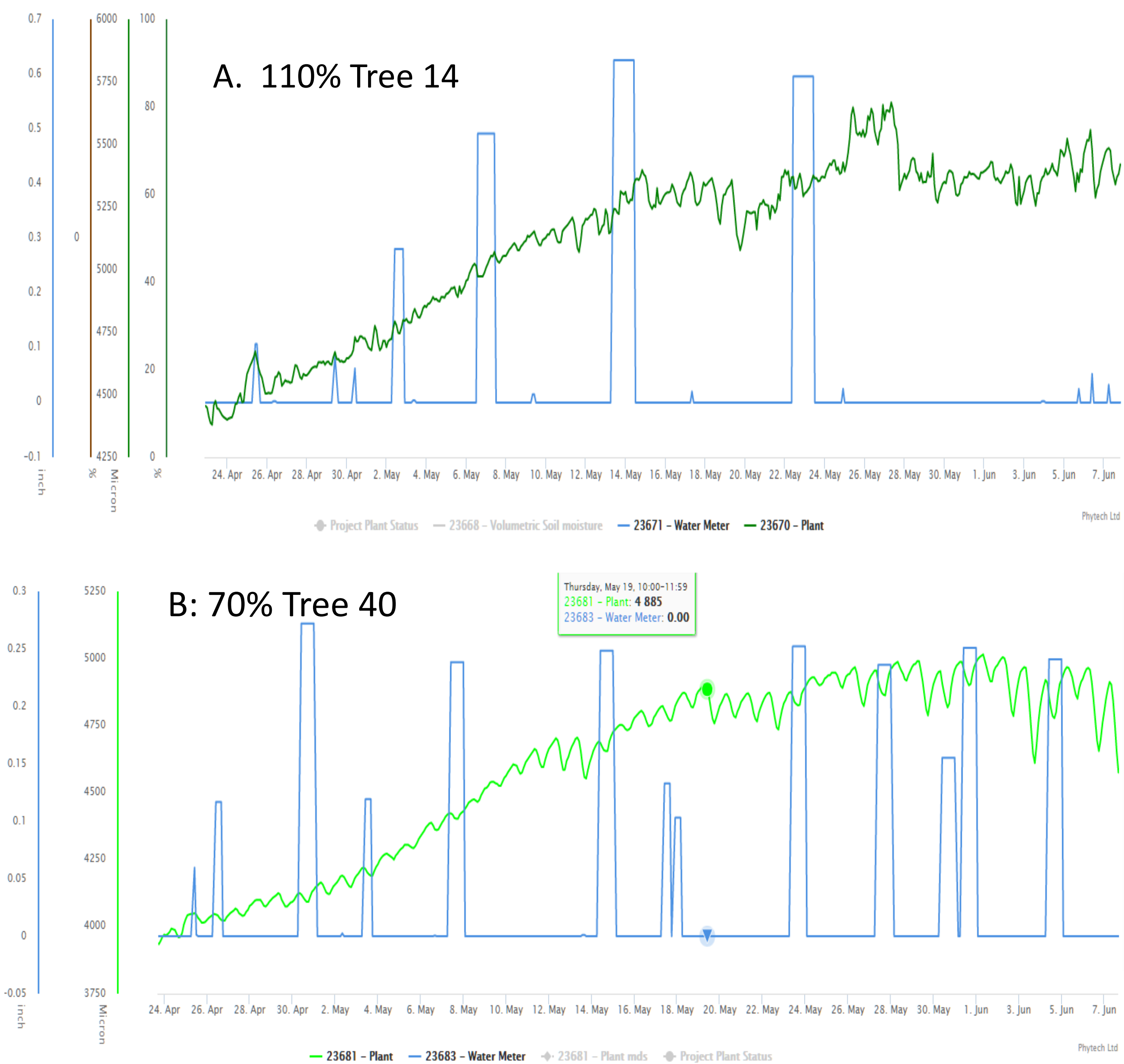

Figure 5 A and B. Individual tree growth and maximum daily shrink/swell from 4/24-6/7 and applied irrigation using a dielectric medium dendrometer attached to the base of the tree and a "reed switch" flowmeter remotely transmitted using Phytech telemetry via cell modem.

The measured MDS for the same day when SWP was measured in the field was the best correlated with SWP ($R^2 = 0.49$) as compared to daily GROWTH or the Phytech calculated PLANT STATUS (**Figure 6).**

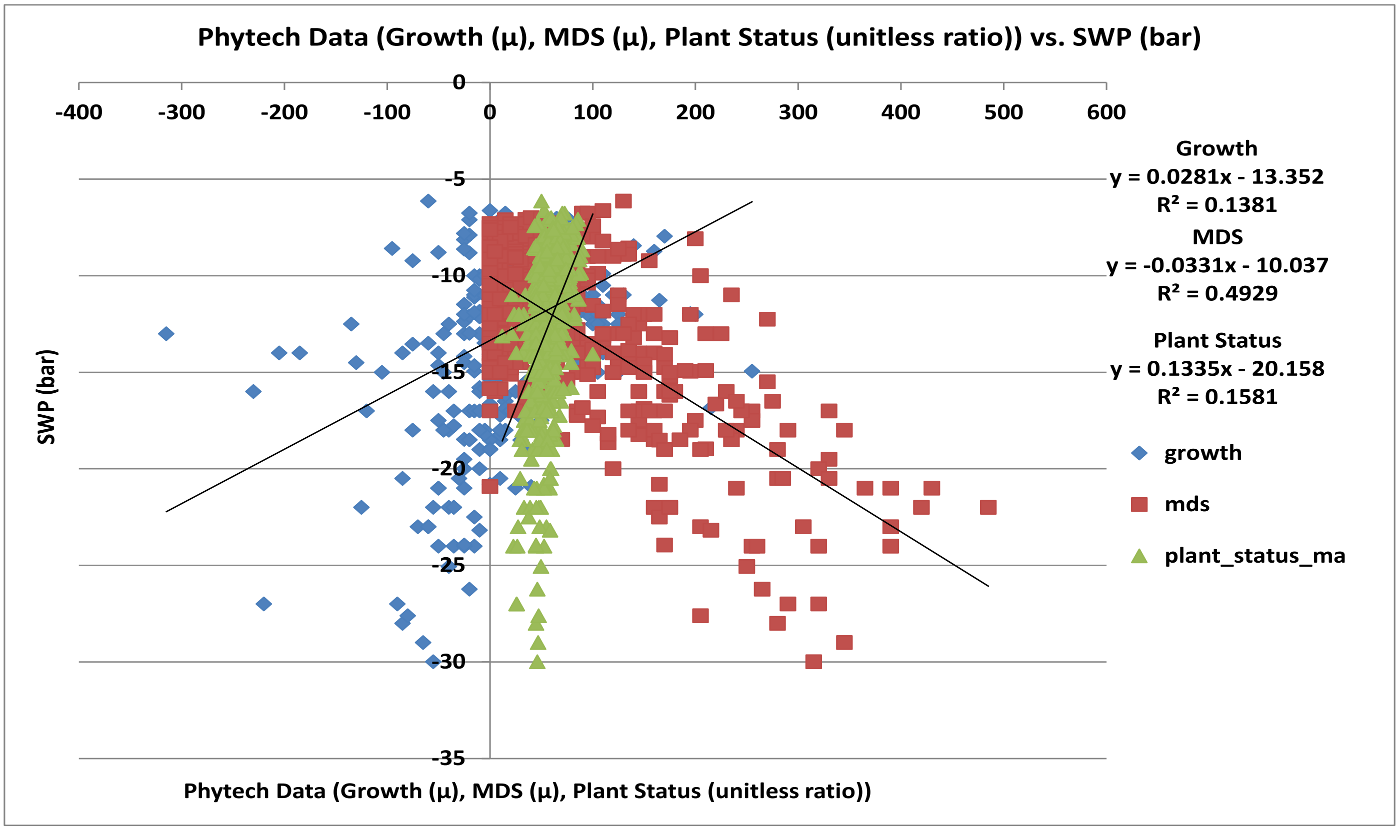

Figure 6. Relationship of Phytech dendrometer estimates of daily GROWTH, maximum daily shrink/swell (MDS) and the proprietary PLANT STATUS calculation to bagged stem water potential (SWP).

Finally, what about the water production function and the relationship of all this stress to actual kernel yield? Even though we have shown a tight relationship with the CERES Conductance, applied water and our experimental treatments, there is only a 23% R^2 for Kernel yield as a function of average Conductance (**Figure 7)** when kernel yield is plotted as a function of applied water the R^2 improves only slightly to 0.24 (**Figure 8)**, but as described in the earlier section by Ken Shackel this is only statistically significant for the difference between the 70% and the 100/110% treatments

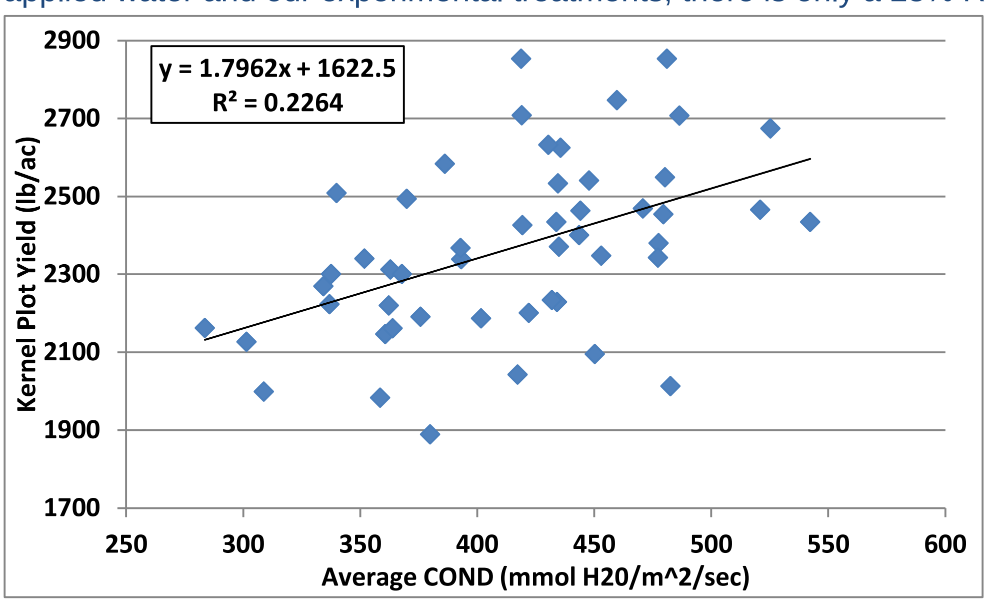

Figure 7. Kernel yield as a function of average CERES CONDUCTANCE from 9 flyovers 3/25-9/22/2015.

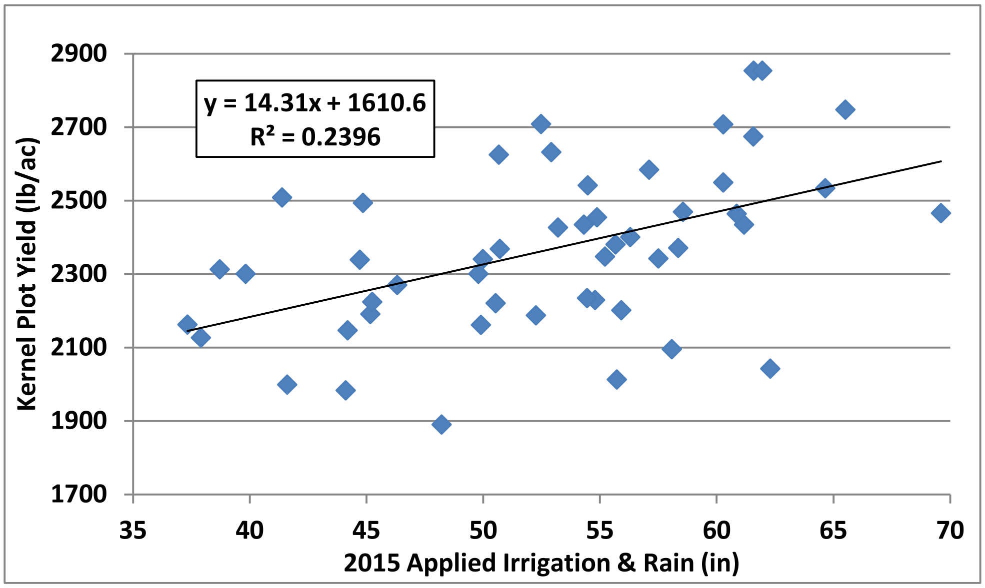

Figure 8. Nonpareil plot kernel yield as a function of whole season applied water.

Lastly, a very detailed calculation was done weekly at the Kern site in an attempt to estimate any leaching and appropriately account for tree wetted rooting volume and thus capture the actual tree ET over 50 monitoring sites outfitted with neutron probe access tubes to a depth of 9.5 feet. Kernel yield as a function of this calculated ET is shown in **Figure 9** – showing about the same R^2 as using the straight applied irrigation plus rainfall.

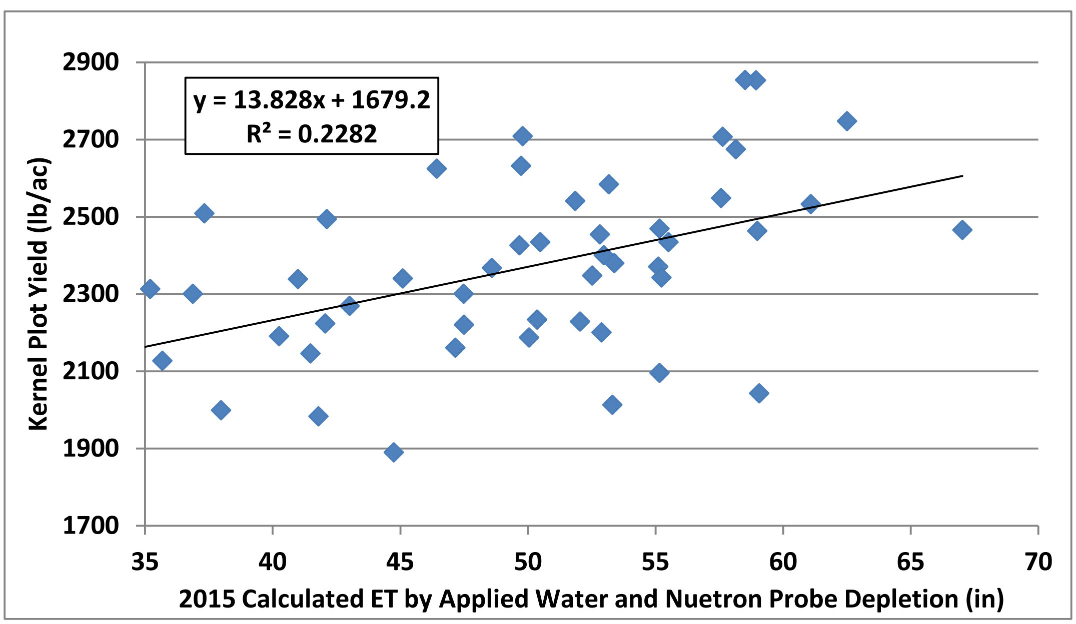

Figure 9. Nonpareil plot kernel yield as a function of neutron probe calculated ET.

CONCLUSION: Mature almonds stress quickly but this doesn't always mean significant yield loss! A variety of plant stress and soil moisture metrics have some relationship to final yield, but none are the perfect predictor of final yield.