Almond Water Production Function

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

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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:

From 2013 to 2017, replicated plots of almonds in commercial orchards located in Tehama, Kern, and Merced counties have been subject to a range of irrigation levels. Depending on the year and site, the 5-year average irrigation plus soil water storage (i.e., estimated total seasonal orchard water use) has ranged from 41-60 inches (74% - 116% ET), but for a given site and year the yield responses to water has been variable. Statistical differences in yield among the different irrigation treatments have only occurred consistently at the Kern site, although for the 5-year averages, both the Kern and the Merced sites have shown a trend for higher yields with greater amounts of water. For these sites we estimate that one inch of water would correspond to an additional 28-30 kernel pounds per acre of production. This is somewhat lower than the estimate of 42 pounds recently obtained by Goldhamer and Fereres (2017). There was no yield response to water at the Tehama site, but a key finding of this project is that differences in yield responses among sites were associated with unique differences in the two main components of yield at each site: nut load and kernel weight. At all sites, including the Goldhamer and Fereres (2017) site, kernel weight always showed a clear increase with increasing water availability. For Goldhamer and Fereres (2017), increases in kernel weight with increased irrigation was the only factor which accounted for increases in overall yield. In the current study, increases in overall yield at Merced were mostly accounted for by increases in kernel weight, but increases in overall yield at Kern were equally accounted for by increases in both kernel weight and nut load, and the lack of yield response at the Tehama site was due to a decrease in nut load with increased irrigation, which compensated for the increase in kernel weight. These results, and those presented in previous reports for

this project, indicate that kernel size responds in a straightforward manner to increasing water availability, particularly during midsummer (June/July), but whether this translates to increased orchard yield will depend on how water availability during these periods, and other periods of the year, will affect nut load. Further research into this question will be needed to maximize ‘crop per drop’ in almonds.

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 to estimate net soil water depletion in each plot. Once irrigation stared, a water balance estimate of total seasonal water use was made by adding applied irrigation to rainfall and net soil water depletion from the start to the end of the season. For plots without a water meter or neutron probe data, treatment average values were used for these 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 tress were obtained. These data were used to calculate yield per unit PAR intercepted.

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 (2017):

<u>Irrigation Amounts, Soil Moisture, and ET.</u> This is the 5th 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. 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 previous years, irrigation at the Kern site started earlier and kept ahead of demand compared to the other sites, but in 2017, the 100% ET treatments at both Kern and Tehama closely matched the calculated irrigation need through July/August (**Figure 1).** As in previous years, the Merced site typically applied less than 100% ET for this treatment, presumably due to a greater availability of stored soil moisture at this site. Different irrigation treatments at all sites applied significantly different amounts of water for the bulk of the season (**Table 2**, applied water), but the trees also used stored soil water during this time (**Table 2**, soil water used) which influenced the final effective range of the irrigation treatments in terms of an effective % ET. Note however that (**Table 2**) only applies to the main irrigation period across sites (March 1 –

September 1), rather than the entire season as shown in (**Figure 1**). As was the case in 2015 and 2016, 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. Despite the expectation that less applied water should result in greater soil water use however, it is interesting to note that there were no statistically significant treatment differences in the use of soil water at any site. Thus far, the only statistical difference between treatments in soil water use occurred in 2015 at Tehama, with the lowest irrigation treatment showing the highest use of soil moisture, and the highest irrigation treatment showing the least, as might be expected.

Plant Response (SWP and PAR). At all sites the general trend was for lower (more stressed) SWP values with less applied water, with Merced showing relatively less irrigation effect than the other two sites (**Table 3**). The general trend in SWP over the season was the same in 2017 as in previous years, with close to baseline values in the spring and monthly averages of -20 bars for the lowest irrigation level mid-season (**Figure 2**). Consistent with the higher soil moisture readings (**Figure 1**, right), Merced had overall higher (less stressed) SWP values for most of the season compared to the other two sites (**Figure 2).** Canopy light interception (percent PAR) only showed statistically significant differences due to irrigation at Kern, with PAR decreasing as irrigation decreased (**Table 3**). In 2015 and 2016 there was a trend toward a consistent reduction in PAR with reduced irrigation at all sites and increased statistical difference, but this trend has not continued.

Plant Response (Kernel Weight and Yield). The influence of irrigation on kernel weight, which was only significant at the Kern site in 2014, was significant at both Kern and Tehama for the remainder of this study (2015-2017), with a clear trend of less kernel weight associated with lower irrigation (**Table 3**). similar trend was apparent in yields, although with a higher degree of overlap between treatments. At the Merced site there was no clear trend in either, with the highest and lowest irrigation treatments only separated by a yield difference of 139 kernel pounds per acre (**Table 3**). Yield per unit PAR (#/PAR, **Table 3**) was not statistically different between the highest and lowest irrigation treatments for any site.

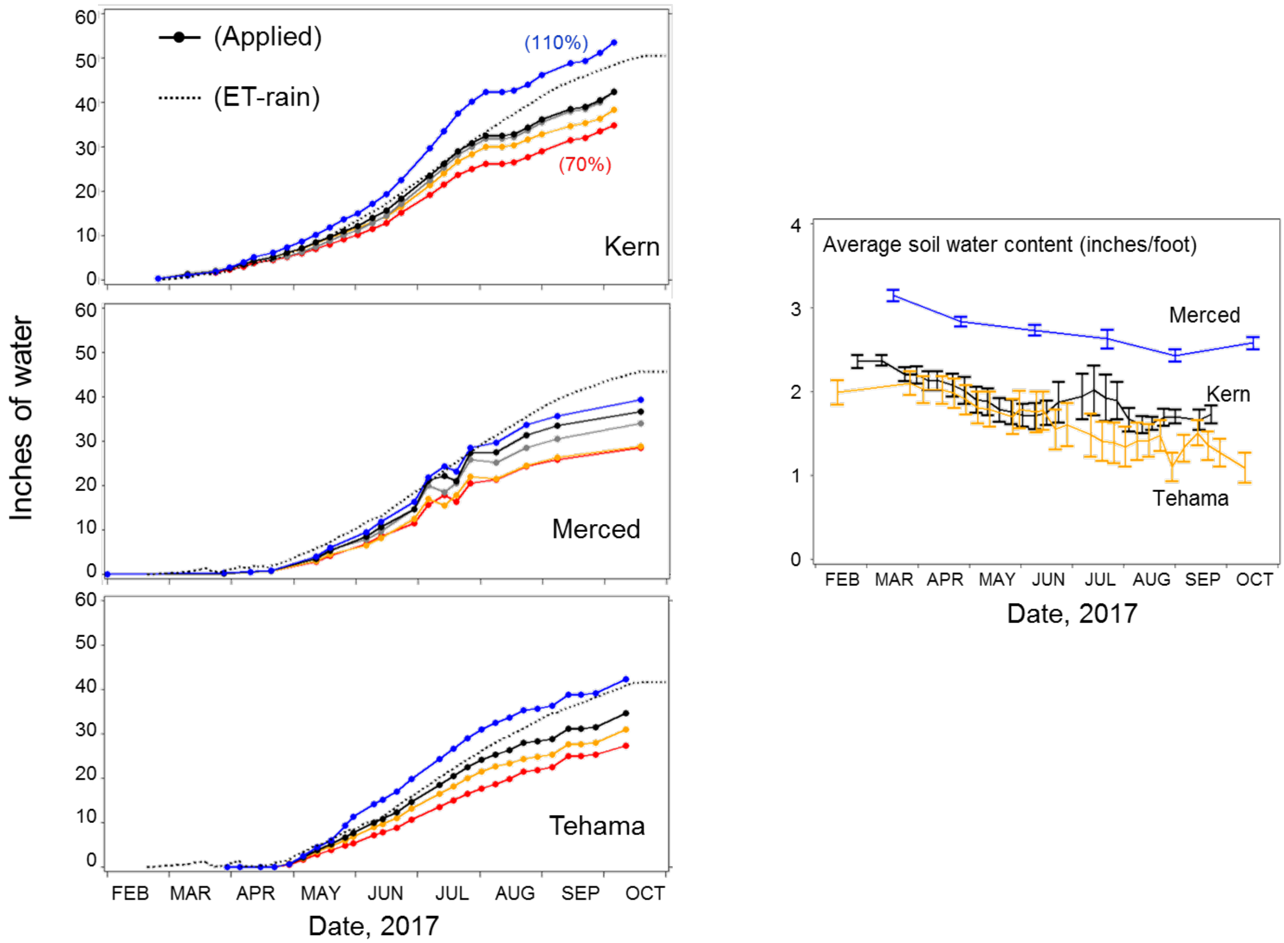

Figure 1. Seasonal pattern of cumulative applied irrigation amounts (left panel) and average soil water content (1' – 9' depth, right panel) at each of the three WPF sites in 2017. For reference, the dashed lines in each graph of the left panel are the calculated water need (ETc – rain) for almond using 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 to the highest irrigation treatment level at each site (only Kern shown for clarity). Note that these are entire seasonal values, rather than the March 1 – September 1 values shown in (**Table 2**). Note also that the variation in applied water for Merced in July was due to the unavailability of water meter data for some blocks on some dates – after this time the cumulative values are accurate. Soil water content was averaged over all treatments, only to illustrate the overall seasonal pattern and differences between sites.

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 need (ET_c – rainfall) for each location for the period March 1 – November 1, 2017.

Location (estimated ET need)	Treatment	Applied water (")	Soil water used (")	Actual %ET_c
Kern (48.4")	110	53.5a	4.9	121a
	100	42.3b	4.7	97bc
	90	42.5b	6.3	100b
	80	38.3bc	6.3	92bc
	70	34.8c	6.2	85c
Merced (45.7")	110	39.4a	3.3	93a
	100	36.7a	5	91a
	90	34.0ab	5	86ab
	80	28.8b	5	74c
	70	28.5b	6.4	76bc
Tehama (40.8")	116	42.4a	6.7	120
	100	34.6ab	7.9	104
	86	30.9b	8.6	97
	74	27.4b	11	94

Table 3. Average (mean) seasonal tree SWP (April - September), midsummer percent light interception (PAR), kernel weight, and yield for the different sites and irrigation treatments (70 – 110 %ET) in 2017. 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	-12.4a	77.7a	1.28a	2,506a	32.2
	100	-13.6a	75.7ab	1.24ab	2,515a	33.2
	90	-14.6a	73.6abc	1.12bc	2,181ab	29.7
	80	-15.0ab	72.0bc	1.10c	2,120b	29.5
	70	-18.7b	70.2c	1.06c	2,038b	40.8
Merced	110	-11.1ab	70.2	1.18	2,124	30.3
	100	-9.9a	73.7	1.16	1,887	25.5
	90	-10.3ab	66.7	1.18	1,820	27.9
	80	-11.1ab	65.9	1.16	1,751	26.5
	70	-12b	67.5	1.17	1,985	29.5
Tehama	116	-9.5a	75.6	1.27a	1,944b	25.9b
	100	-11.3b	68	1.21ab	2,199ab	32.3ab
	86	-12.1b	70.2	1.20ab	2,309a	33.6a
	74	-14.0c	69.7	1.15b	2,146ab	30.9ab

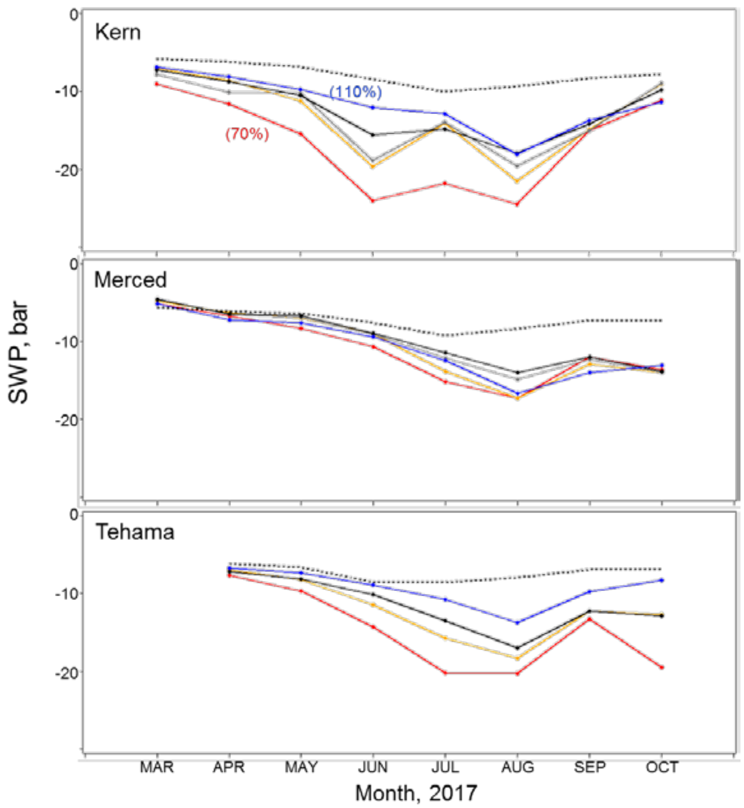

Figure 2. Seasonal pattern of monthly average stem water potential (SWP) for each treatment at each location, with the highest and lowest irrigation treatments indicated for Kern (other sites were also consistent with the irrigation treatments). Also shown for reference is the fully irrigated (non-stressed)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

Results and Discussion (5-year summary):

Except for the pre-treatment year (2012), yields have varied between about 1,200 and 3,500 kernel pounds per acre for the 3 sites, with some variation from year-to-year at all sites (**Figure 3**). Differences in yield that were consistently related to difference in irrigation have not always been apparent. Due to technical difficulties at each site as well as differences within sites and between sites and years in the use of stored soil moisture, the effective irrigation treatments (expressed as a % of ET for each site) always covered a more limited range than the target treatments were intended to cover (**Table 4**). However, on average, an effective irrigation difference of 13” to 19” of water was achieved from the lowest to the highest irrigation at all sites, and at all sites the 5-year average yields have been highest for the most irrigation and lowest for the least (**Table 4**).

Overall kernel yield is the result of both numbers of kernels per acre (nut load) as well as individual kernel weight, and (**Table 5)** summarizes these effects for the 5-year average of each treatment at each site (**Table 5a**), and for the relative effect from the high to the low irrigation level at each site (**Table 5b**). All sites showed a statistical effect of irrigation treatments on %PAR, which may be important in overall tree productivity, but while this effect was consistent (**Table 5a**), it was not large. The Tehama site showed a statistically significant effect of irrigation on kernel weight, but not yield or nut load (**Table 5a**). The Kern site showed a statistically significant effect of irrigation on kernel weight, yield, and nut load, and the Merced site showed no statistically significant effect on any of these yield factors (**Table 5a**).

When these effects were expressed as a relative change from high to low irrigation (**Table 5b**) the differences between sites in the overall response of yield to irrigation was clearer. All sites

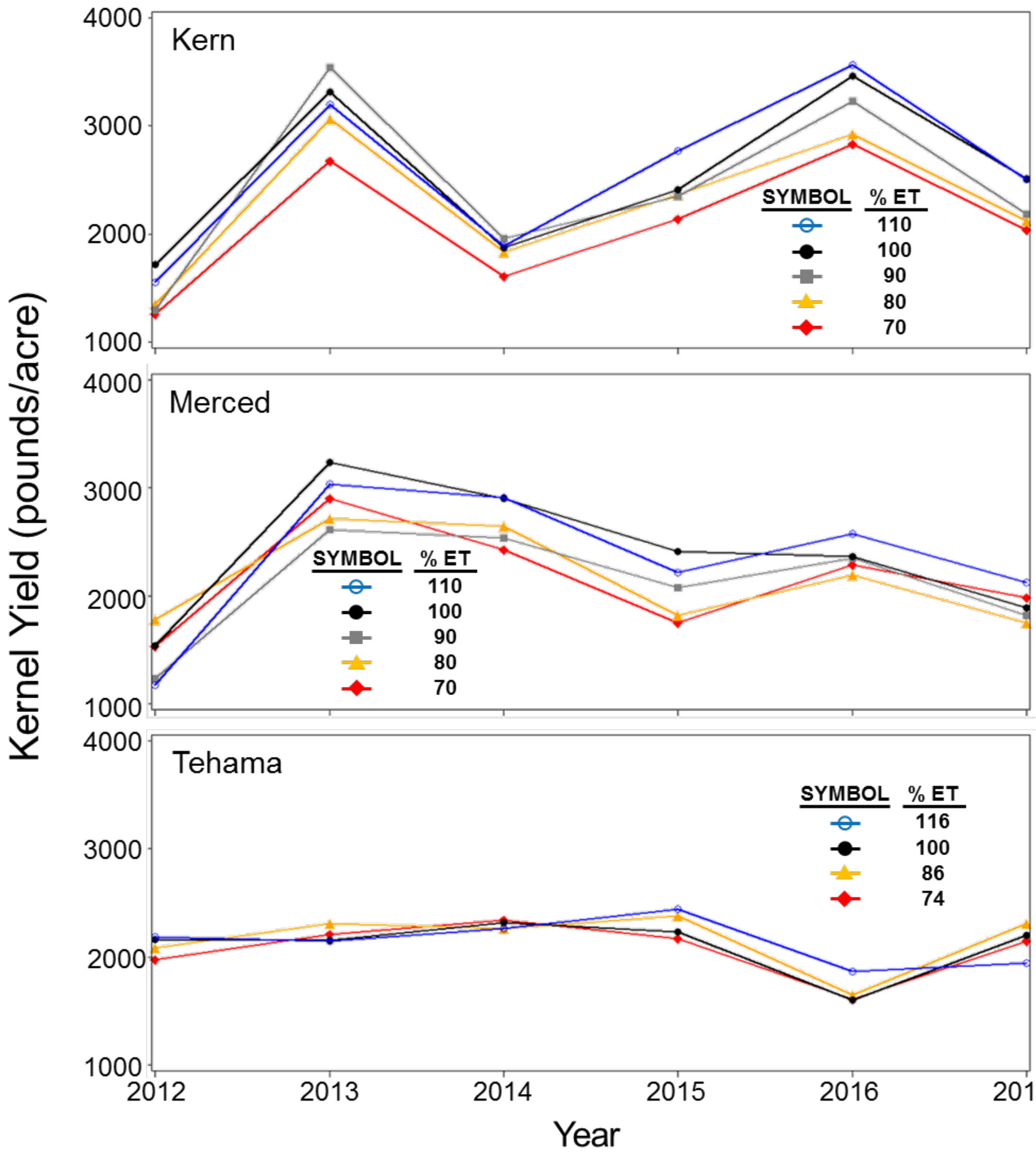

Figure 3. Average annual yields in each treatment from 2012, prior to any treatment imposition, to 2017, after 5 years of treatment imposition, at each location.

Table 4. Summary of individual year kernel yields as well as the 5-year average yield from each of the irrigation treatments at each site. Also shown is a comparison of the experimental target irrigation level (% ET) and the effective (Irrigation + Soil Water Use) %ET (in percent as well as inches) over the 5 years for each treatment and site. Statistically significant differences are shown in bold, with means followed by the same letter being not statistically different.

			Yield (Kernel pounds/acre)					
Site	Target % ET	5 years average effective %ET (inch)	Year					5-year average
			2013	2014	2015	2016	2017	
Tehama	116%	116% (57")	2143	2260	2440	1860	**1940b**	2130
	100%	107% (52")	2150	2315	2230	1600	**2200ab**	2100
	86%	93% (45")	2310	2260	2380	1650	**2310a**	2180
	74%	89% (43")	2210	2340	2170	1610	**2150ab**	2090
Merced	110%	104% (54")	3040	2910	2220	2580	2120	2570
	100%	96% (50")	3240	2900	2410	2370	1890	2560
	90%	89% (46")	2620	2540	2080	2350	1820	2260
	80%	82% (43")	2720	2640	1820	2190	1751	2220
	70%	79% (41")	2900	2420	1750	2280	1980	2270
Kern	110%	107% (60")	**3200ab**	1890	**2770a**	**3560a**	**2510a**	**2790a**
	100%	93% (52")	**3310ab**	1870	**2410b**	**3470a**	**2520a**	**2720a**
	90%	94% (52")	**3540a**	1960	**2350b**	**3230ab**	**2180ab**	**2650ab**
	80%	85% (47")	**3060ab**	1840	**2370b**	**2920b**	**2120b**	**2460bc**
	70%	74% (41")	**2670b**	1610	**2140b**	**2830b**	**2040b**	**2260c**

Table 5a. Summary of 5-year average kernel yields, yield components (number of kernels per acre and weight per kernel), and canopy % PAR, ranked in order of effective %ET treatment. Kernel yield is in pounds per acre, number of kernels (nut load) is millions of kernels per acre, and kernel weight is grams per kernel. Statistically significant differences are shown in bold, with means followed by the same letter being not statistically different.

	5 Year average values				
Site	Effective %ET	Yield	M Kernels/acre	Grams per kernel	%PAR
Tehama	116%	2130	0.783	**1.24a**	**68a**
	107%	2100	0.802	**1.20ab**	**65b**
	93%	2180	0.844	**1.19b**	**65b**
	89%	2090	0.843	**1.14c**	**65b**
Merced	104%	2570	1.052	1.13	**68ab**
	96%	2560	1.024	1.12	**69a**
	89%	2260	0.945	1.09	**64c**
	82%	2220	0.938	1.09	**63c**
	79%	2270	1.017	1.04	**65bc**
Kern	107%	**2790a**	**1.175ab**	**1.09a**	**74a**
	94%	**2650ab**	**1.177a**	**1.03b**	**71b**
	93%	**2720a**	**1.144ab**	**1.10a**	**72ab**
	85%	**2460bc**	**1.119ab**	**1.02b**	**70bc**
	74%	**2260c**	**1.068b**	**0.99b**	**69c**

Table 5b. Relative effect of a decrease (-) or increase (+) from high to low irrigation (applied water) on kernel yield, number of kernels, kernel weight, and %PAR.

	% Effect (High to Low Irrigation Level)				
Site	Water	Yield	# Kernels (nut load)	Gram/Kernel	PAR
Tehama	-24.5%	-1.9%	+7.7%	-8.1%	-4.4%
Merced	-24.1%	-11.7%	-3.3%	-8.0%	-4.4%
Kern	-31.7%	-19.0%	-9.1%	-9.2%	-6.8%

were subject to meaningful (25 – 30%) reductions in effective water availability (**Table 5b**), and all exhibited similar reductions in canopy light interception (PAR), but sites differed greatly in both the magnitude and direction of the effects on overall yield and yield components. For instance, the yield reductions with reduced water at the Kern site were about equally due to reductions in both nut load and kernel size (**Table 5b**), but the yield reductions at the Merced site were mainly due to reductions in kernel size, and the lack of a yield effect with reduced water at the Tehama site was the result of opposite effects of about equal magnitude: reductions in kernel size but increases in nut load as water was reduced (**Table 5b**). Yield effects are compared between sites and to literature data based on inches of water as well as % ET in (**Table 6**). Goldhamer and Fereres (2017) reported a 42 lb./ac increase in yield per inch of water (22 lb./ac per % ET), roughly like the values that we found in Kern and Merced (**Table 6**). However, the sources of the yield effects were different at different sites, with Goldhamer's yield effects entirely attributed to kernel weight, compared to both kernel weight and load effects at Kern and mostly (but not entirely) kernel weight at Merced (**Table 5b**).

Table 6. Summary of overall irrigation effects over the 5-year study at each site and a comparison to the kern county almond water production function results of Goldhamer and Fereres, 2017 ("Kern G&F").

Site	Observed increase (+) or decrease (-) in yield (kernel pounds per acre) per effective:		Interpretation
	Inch of water	% ET	
Tehama	-0.7	-0.3	Positive kernel weight effects are being canceled by negative nut load effects.
Merced	28	15	Yield increase coming mainly from an increase in kernel weight, and a small increase in nut load.
Kern	30	17	Yield increase coming equally from increases in kernel weight and nut load.
Kern (G&F)	42	22	Yield increase coming entirely from increases in kernel weight – possible drop in nut load at the highest irrigation.

<u>Conclusions:</u>

- The response of almond yield to irrigation will likely be orchard/site-specific.
- For most sites it is reasonable to assume that kernel weight will increase with increasing water, but overall yield effects may be positive or negative, depending on how the increased water affects nut load.
- Based on this as well as an independent almond study, the water productivity may range from essentially no response, to 30-40 kernel pounds per acre per inch of water, or about 15-20 kernel pounds per acre per % of ET.
- Future research should focus on determining the sensitivity of both kernel weight and nut load to irrigation management at different times of the crop cycle.

Research Effort Recent Publications:

None.

References Cited:

Goldhamer DA, Fereres E. 2017, Establishing an almond water production function for California using long-term yield response to variable irrigation. Irrig. Sci. 35:169-179.