Development of a Nutrient Budget Approach and Optimization of Fertilizer Management in Almond

Project No.: **12-PREC2-Brown**

Project Leader: Patrick Brown
Department of Plant Sciences, M-S 2
UC Davis
One Shields Avenue
Davis, CA 95616
530.752.0929
530.752.8502 (fax)
phbrown@ucdavis.edu

Project Cooperators and Personnel:
Sebastian Saa and Saiful Muhammad, Department of Plant Sciences, UC Davis
Blake Sanden, Farm Advisor - Kern County
Roger Duncan, Farm Advisor - Stanislaus County
Brent Holtz, Farm Advisor - Madera County
Bob Beede, Farm Advisor - Kings County
Franz Niederholzer, Orchard Systems Farm Advisor - Colusa, Sutter & Yuba Counties
Paramount Farming Company
Yara Fertilizer Company
Emilio Laca, Professor, UC Davis

Objectives:

- Determine the degree to which leaf nutrient status varies across a range of representative orchards and environments.
- Determine the degree to which nutrient status varies within the canopy and within the year.
- Validate current CVs and determine if nutrient ratio analysis provides useful information to optimize fertility management.
- Develop a phenology and yield based nutrient model for almond.
- Develop fertilizer response curves to relate nutrient demand with fertilizer rate and nutrient use efficiency.
- Determine nutrient use efficiency of various commercially important nitrogen (N) and potassium (K) fertilizer sources.
- Develop and extend an integrated nutrient BMP for almond.

Interpretive Summary:

The primary goals of this research were to 1) conduct a systematic examination of leaf sampling protocols and their use in decision making and to develop early season sampling protocols, and 2) to determine the response of almond to various rates and sources of nitrogen (N) and potassium (K) fertilizers, to develop nutrient demand curves, to conduct a long term assessment of nutrient use efficiency and to develop more refined fertilization recommendations.

The first goal was addressed in almond orchards in four locations in California (Arbuckle, Belridge, Madera and Modesto). Leaf and nut samples were taken at various times throughout the season to determine the degree of variability in tissue nutrient concentrations over time, space and within tree canopies. This was used to establish sound leaf sampling protocols. Results demonstrated that there is a high degree of consistency in patterns of change in tissue nutrients over time and that early season sampling can be used to diagnose deficiencies and nutrient demands. July leaf nitrogen content (and likely other nutrients) can be well predicted with an early season (April) sampling.

The second project goal was addressed in a fertigation trial at Belridge, Kern County, CA. This experiment aimed to develop a phenology and yield based nutrient model for almond to develop fertilizer response curves that relate nutrient demand with fertilizer rate and nutrient use efficiency, and to determine nutrient use efficiency of various commercially important N and K fertilizer sources. Findings from both project components are being integrated to develop nutrient best management practices for almond. Treatments in the fertigation trial consisted of five rates of nitrogen (0, 125, 200, 275 and 350 lbs/ac), supplied by two commercially important sources of nitrogen, UAN 32 and CAN 17. The zero N control was introduced in fall 2011 as a split plot in the previously 125 lbs treatment. There were three treatments for potassium rates (100 lbs/ac, 200 lbs/ac and 300 lbs/ac) and three sources of potassium (SOP, SOP+KTS and KCl).

Annual nutrient export in harvested fruit was determined in all years of this experiment. In years 2009 through 2011 nitrogen in fruit at harvest represented >85% of whole tree nutrient fluxes. Total N export from the orchard in harvested crop is proportional to the total size of the crop and the nutrient concentration in that crop, which varies in proportion to the ratio of fertilization rate to total annual N demand. In trees provided just adequate N to achieve maximal yield (275 lbs/ac in this experiment in years 2009-2011), each 1000lbs of kernel yield at harvest exported from the orchard 59 to 74lbs N while phosphorus and potassium export by 1000lbs kernel yield at harvest ranged from 7.5lbs to 9lbs and 65lbs to 85lbs respectively. Mean of sulfur (S), calcium (Ca) and magnesium (Mg) export by 1000lbs kernel yield was 2.3lbs, 7lbs and 4.5lbs respectively. The accumulation of micronutrients was also determined, but is not presented in this report. Fertilizer N application above or below the 275 lbs/ac rate altered N concentrations in fruit and hence N export in fruit per 1000lbs kernel yield. In 2012, yield was exceptionally low resulting in a substantial excess N application in all treatments and an increase in fruit nutrient concentration and N export in fruit per 1000lbs kernel of up to 87lbs was observed. Across all years and treatments an average N export value of 68 lbs N per 1000lbs kernel was recorded.

Sequential analysis of annual and perennial organs demonstrated that the majority of whole tree macro- and micronutrient uptake occurs between anthesis [bloom] and kernel fill with 30% of total N uptake occurring before 40 days after full bloom (DAFB) and 80-90% of the total N being accumulated by 130 DAFB. Data on whole tree nutrient demand and the in-season accumulation of nutrients in annual and perennial tissues can be used as a basis for managing fertilization in almond.

Nutrient use efficiencies of nitrogen (N) and potassium (K) under differential fertilization rates and sources were also estimated in this project. Nitrogen use efficiency (NUE) calculated as N exported from the orchard in fruits and N accumulated in perennial tissues for growth over N applied in fertilizer and contributed by soil, ranged from 63% to 104% under sprinkler irrigation and 60% to 114% under drip irrigation for the N rate of 275lbs/ac in different years. In these experiments an N rate of 275lbs/ac was the lowest N application rate that resulted in maximal productivity. NUE declined as N application rate increased. NUE was not affected by N sources. Potassium use efficiency (KUE) was highest for 100lbs/ac K application rate and declined as K application rate increase. Apparent KUE exceeded 100% in most treatments and most years and increased with tree age for all K rate treatments. K sources only showed significant difference in KUE in 2010 where K application with SOP+KTS was higher than with other K sources. A KUE of over 100% for all K rates suggests that trees are accessing soil mineral reserves.

Nutrient concentrations and biomass of all major organs of mature field grown almond trees was collected by whole tree excavation, sequential tissue sampling and nutrient analysis in trees grown under four nitrogen rate treatments. The amount of nutrient accumulated in perennial organs over one year (2012) was determined as the difference between the total tree nutrient pool in dormant trees prior to, and at the completion of a single season. The dynamics of nutrient remobilization in perennial tissues during early season growth, and the accumulation of nutrients in perennial tissues were determined by sequential coring, tissue sampling, biomass estimation and whole tree excavation. Nutrient resorption from leaves was determined from multiple seasonal leaf samples. All measurements were replicated in trees of differing N fertilization regimes. In 2013 more data have been collected and sent to the laboratory for their nutrient content

The combination of nutrient budget determination, nutrient response information, improved sampling and monitoring strategies, and yield determination provide a theoretically sound and flexible approach to ensure high productivity and good environmental stewardship.

Materials and Methods:

Variability Trial

At each site samples were collected for a period of 3 years from 8 to 10 year old micro-sprinkler irrigated (one drip irrigated) almond orchards of good to excellent productivity planted to Nonpareil (50%). For each of the 4 almond sites (Arbuckle, Belridge, Madera and Modesto), plots were 10-15 acre contiguous blocks. Leaf and nut samples from 114 trees were collected at 5 times during the season. Sample collection was spaced evenly over time from full leaf expansion to harvest. As a phenological marker, days past full bloom and stage of nut development were noted. Light interception, tree water status, and individual yields of these trees were also measured.

A standard leaf sampling protocol was used to determine nutrient concentrations in samples of exposed, non-fruiting spurs (NF), as well as leaves from fruiting spurs with 1 and 2 fruit (F1 and F2, respectively) to explore the sensitivity of different sampling methods as indicators of tree nutrient demand. In 2010 F1 was discarded and tissue samples were collected from NF and F2. To establish seasonal nutrient accumulation and nutrient export, composite nut samples were collected from each site. Both leaf and nut samples were dried and ground prior to sending them to the DANR (Agriculture and Natural Resources) Analytical Laboratory located on the UC Davis campus.

In 2011 the spatial and temporal variability of the leaf nutrient content was estimated and statistical models were performed to answer the following questions:
1. Can we sample in April and predict July nitrogen content?
2. Can we predict the proportion of trees below certain critical value in July?
3. What is the best sampling method?

In 2012 we validated the models obtained in 2011 by selecting 6 new orchards representative of the major production areas of California's Central Valley.

Fertigation Trial
The original fertigation rate and source experiment was established in a Paramount Farms almond orchard at Belridge, Kern County, California under fan jet and Drip irrigation systems. Each of the 12 treatments (**Table 1**) was replicated in five or six blocks with 15 trees per block. Treatments consisted of four rates of nitrogen (125, 200, 275 and 350 lbs/ac), supplied as two commercially important sources of nitrogen (Urea Ammonium Nitrate 32% [UAN 32] and Calcium Ammonium Nitrate 17% [CAN 17]). Potassium was applied at three rates (100, 200 and 300 lb/ac as K) and supplied by three sources of potassium (Sulphate of Potash [SOP], SOP + Potassium Thiosulphate [KTS] and Potassium Chloride [KCl]). 60% of the potassium in K rate treatments was applied as SOP in early February, while the remaining 40% was applied as KTS in four fertigation cycles. Nitrogen was applied in four fertigation cycles with 20%, 30%, 30% and 20% of total nitrogen supplied in February, April, June and October, respectively. Fifteen trees and their immediate 30 neighbors, in two neighboring orchard rows were treated as one experimental unit. All data were collected from six trees in the middle row. A total of 768 experimental trees were selected for this experiment. Leaf and nut samples were collected from individual trees in April, May, June, July and August. A total of 5400 leaf and nut samples were collected and analyzed for N, P, K, Ca, S, Mg, boron (B), zinc (Zn), copper (Cu), manganese (Mn) and iron (Fe) at the DANR Lab at UC Davis. The crop was harvested in August and individual tree yields were determined for all data trees. Yield of the remaining nine non-data trees in the data trees row was also determined to get average plot yield of fifteen trees. Four-pound samples were collected from two data trees each in each replicate to determine crack out percentage (turn over) and oven dry weight. Twenty nuts were collected at harvest from each experimental tree to determine the ratio of kernel to shell/hull and the partitioning of nutrients.

Table 1. Fertilization treatments

Treatment	N source	N amount (lbs/ac)	K source	K amount (lbs/ac)
A	UAN32	125	60% SOP / 40% KTS	200
A1*	N.A.	0	60% SOP / 40% KTS	200
B	UAN32	200	60% SOP / 40% KTS	200
C	UAN32	275	60% SOP / 40% KTS	200
D	UAN32	350	60% SOP / 40% KTS	200
E	CAN17	125	60% SOP / 40% KTS	200
F	CAN17	200	60% SOP / 40% KTS	200
G	CAN17	275	60% SOP / 40% KTS	200
H	CAN17	350	60% SOP / 40% KTS	200
I	UAN32	275	60% SOP / 40% KTS	100
J	UAN32	275	60% SOP / 40% KTS	300
K	UAN32	275	100% SOP	200
L	UAN32	275	100% KCl	200

**From fall of 2011 a zero N treatment (A1*) was setup using the half of the trees that belonged to the treatment A.*

Results and Discussion:

Variability Trial

In these well managed and visually uniform orchards there is substantial variability in nutrient concentration between orchards (**Figure 1**) and within orchards (**Figure 2**) that needs to be captured to correctly obtain the true mean of the nutrient being sampled and allow correct interpretation of them. This detailed analysis of data has allowed us to estimate 'typical' field variability in California orchards of this type and to use that data to determine best sampling strategies. Thus, data from these field sites has been used to calculate the number of pooled leaf samples that is required to accurately determine the true field nutrient mean. **Table 2** represents the result of this analysis, accepting that growers usually collect one pooled sample per orchard.

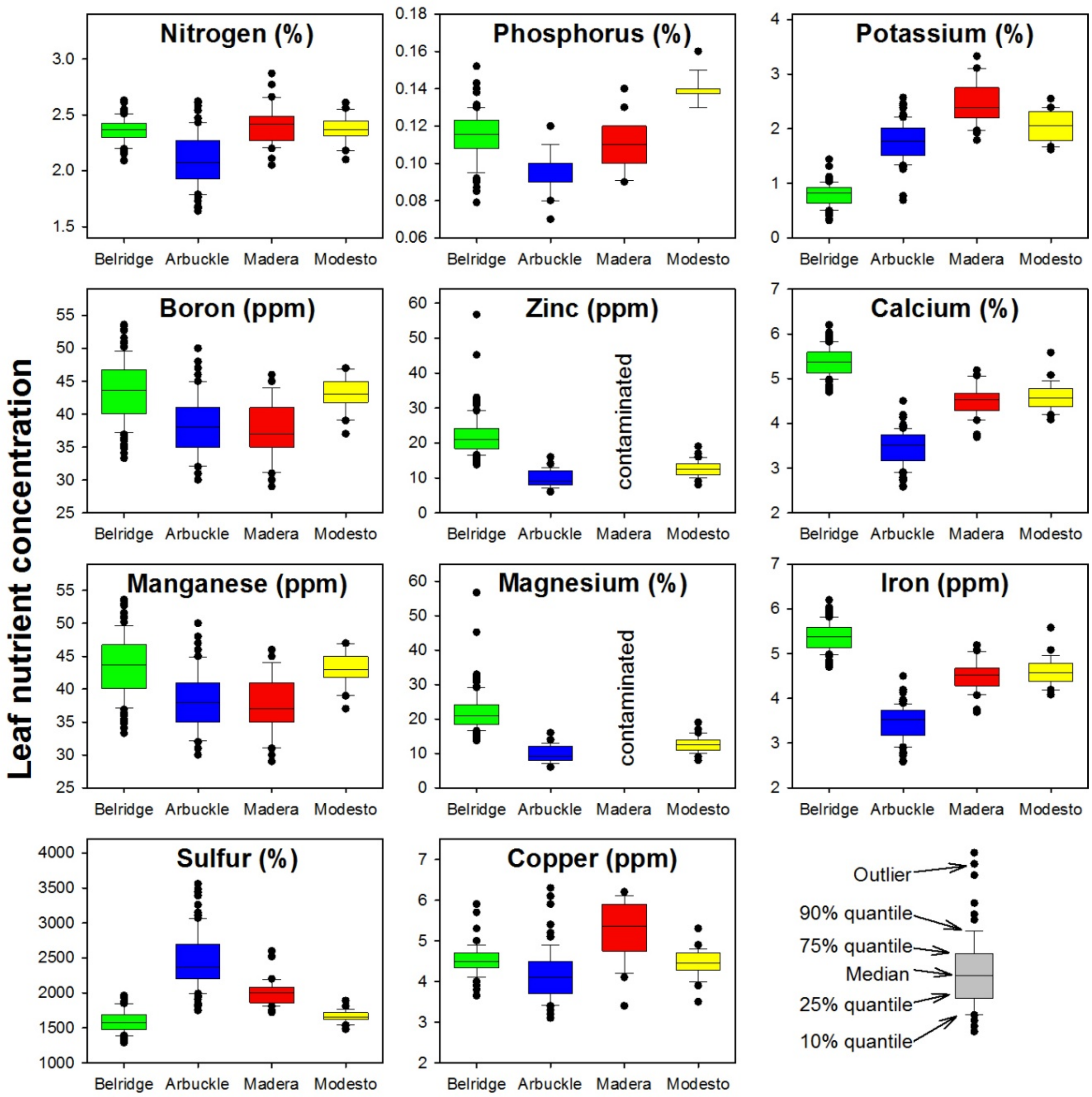

Figure 1. Variability in leaf nutrient concentrations within and among almond orchards sampled in July. Non-fruiting spur leaf samples collected from 114 individually sampled trees at 4 sites.

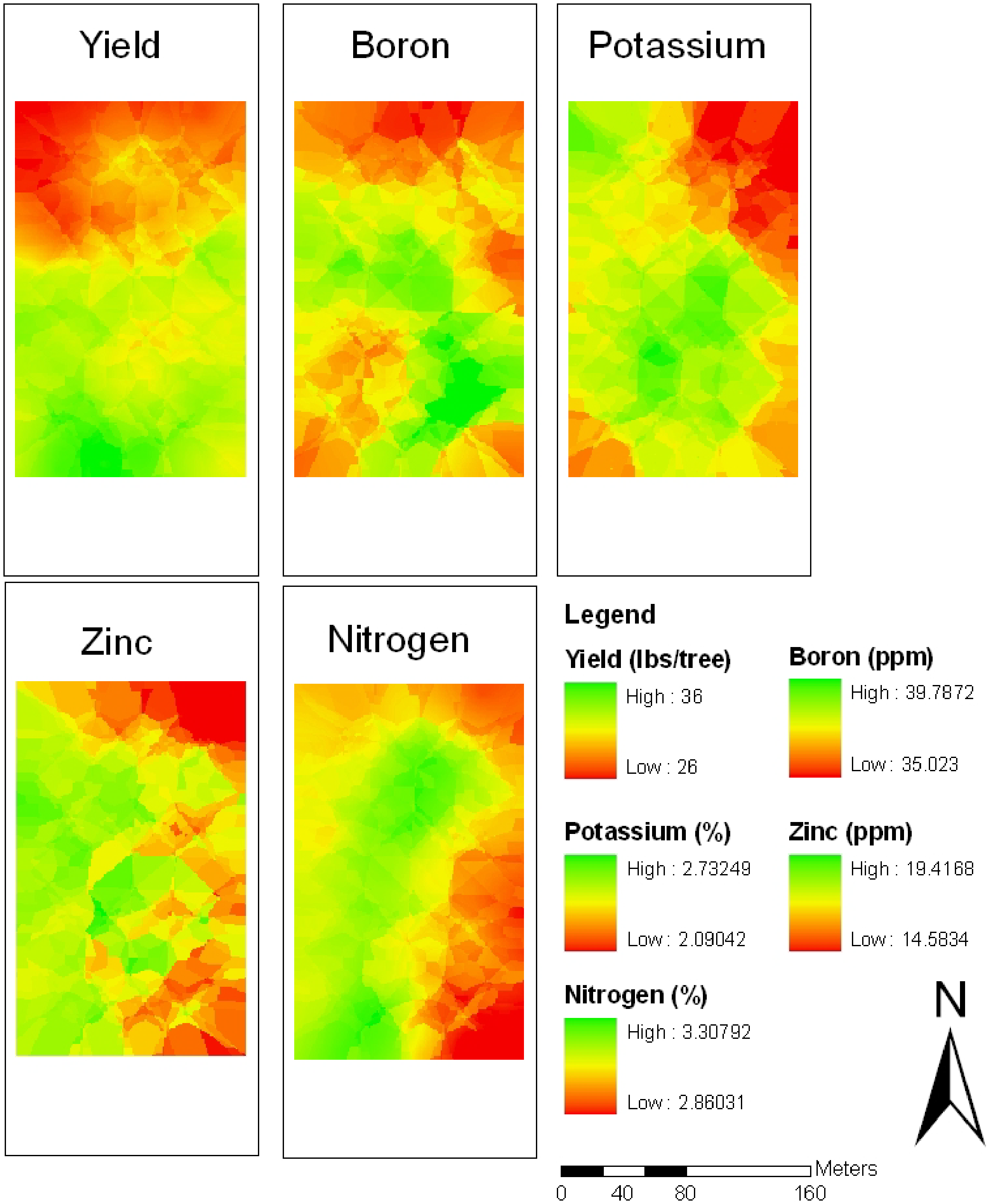

Figure 2. Spatial leaf nutrient content recorded in May and the current season yield in a representative California almond orchard.

Table 2. Numbers of trees required to obtain average July N predictions at a desired degree of confidence and interval length.

Desired margin of error	**Numbers of trees to be sampled**	
N %	Desired Confidence level: 90%	Desired Confidence level: 95%
0.2	29 trees to be sampled	82 trees to be sampled
0.3	9 trees to be sampled	15 trees to be sampled

In addition to determining optimum field sampling strategies, the detailed analysis of data from four well-managed and visibly uniform sites over four years also allows us to extrapolate from a well collected leaf sample to estimate the percentage of the field that will be above a particular established critical value. For example the established critical value is 2.2% N in July for almonds (**Table 3**); using this knowledge and the sampling strategies we have established, it is possible to better understand the distribution of tree nutrient status in the orchard.

Table 3. Relationship between July leaf tissue N concentrations in almond samples collected according to previously described sampling methods (this report) and percentage of trees in the orchard that will exceed the specified critical value of 2.2% N.

Relationship between July leaf tissue N concentration and percentage of the trees exceeding the critical value of 2.2%										
July N (%)	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9
% of Trees Above 2.2%	6.6	22.6	50.0	77.4	93.4	98.8	99.9	100.0	100.0	100.0

Different statistical models were performed to correctly predict July Leaf N % using an April leaf sample. All the models received two types of validation. Model performance was evaluated by comparing predictions and observations for individual trees, and by comparing predictions based on April predictor values against observed average leaf N concentrations in July for each orchard and year ("model verification"). The six models were finally validated by comparing orchard-level predictions with observed averages in an additional set of orchards measured in 2012 ("model validation"). **Figure 3** shows the results of the best model.

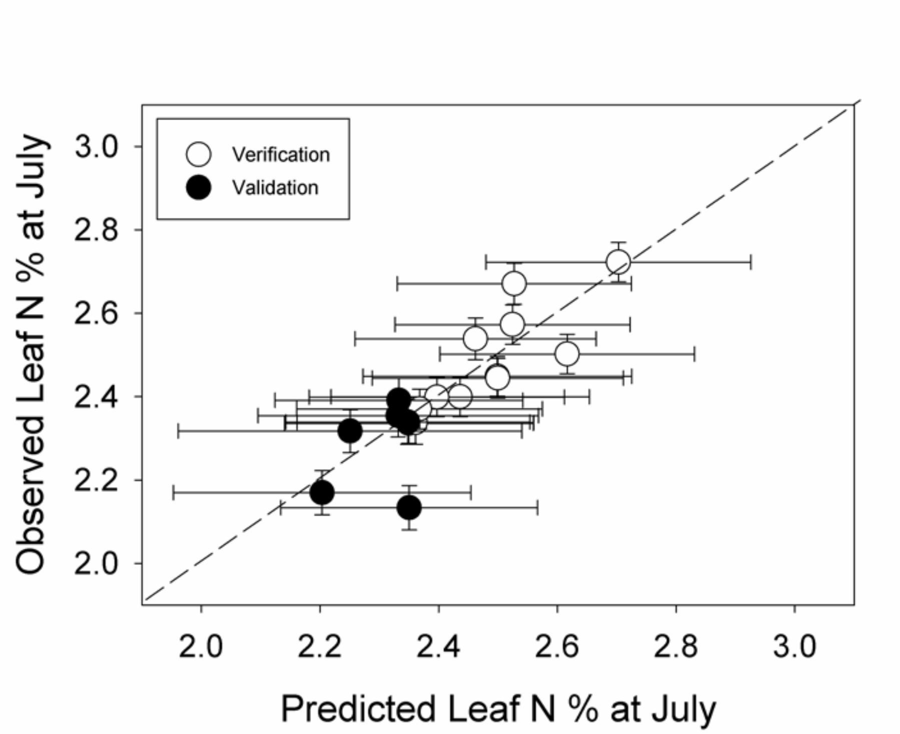

Figure 3. Verification (open circles) and validation (filled circles) of the best model performance. Dashed line is the 1:1 concurrence between predicted and observed values. Bars show the 95% confidence intervals. Circles represents average N % observed in July (y axis) and predicted by the model (x axis) with a sample of 30 pooled trees for the 18 site-year combinations in the study.

Thus, an improved method of leaf sampling and fertilization management has been developed that utilizes April leaf sampling and yield estimations to predict N demand and to allow for in-season fertilizer adjustments.

<u>Sampling Protocol</u>

The following leaf-sampling method recognizes that growers generally collect one combined leaf sample per orchard, and is effective in orchards of average variability. If the orchard to be sampled has substantial variability, then the sampling protocol should be repeated in each zone, and N should be managed independently in each of zone. Management of N in each zone can be achieved through separation of fertigation systems or by supplemental soil or foliar fertilization in high-demand areas. Efficient management of N requires that every orchard that differs in age, soil, environment or productivity should be sampled and managed independently.

Almond Sampling Method (**UC Davis Early-Sampling Protocol or 'UCD-ESP'**)

For each orchard/block or sub-block that you wish to have individual information on, do the following:

- Sample all the leaves of 5–8 non-fruiting, well-exposed spurs per tree at approximately 43 +/-6 days after full bloom when the majority of leaves on non-fruiting spurs have reached full size. In the majority of California orchards, this corresponds to mid-April. Should sampling at this date not be possible, then please note the date of sample collection on the sample bag.

- Collect leaves from 15–30 trees per orchard. Combine all leaves in a single bag for submission to a reputable laboratory. Each sampled tree must be at least 30 yards apart. A minimum of 100 leaves per sample bag is required.
- Send the samples to the lab and ask for a FULL NUTRIENT ANALYSIS (N, P, K, B, Ca, Zn, Cu, Fe, Mg, Mn, S) and application of the UCD-ESP program.

Summary:

- These techniques have been validated only for the Nonpareil variety in orchards that are at least 8 years old. If other cultivars are used, please note which cultivar was sampled on the sample bag. Method development for other cultivars is under way. However, this current approach will result in valuable information for any cultivar, as cultivar-specific nutritional requirements likely do not vary significantly.
- Repeat for all orchards and orchard regions that differ in productivity, age or soil type. Identify your areas of low performance, and collect samples from them independently.
- Label all samples well with collection date, field number, cultivar, and within field location if needed. Please note if foliar fertilizers have been applied.

Fertigation Trial

The project was conducted to develop nutrient demand curves and whole tree budgets for macro and micronutrients in a commercial almond (*Prunus dulcis*) orchard managed under a variety of N and K fertilization regimes. Experiments and measurements were replicated in drip and fan jet irrigated orchards over a 5 year period, 2008 through 2012. Whole tree nutrient dynamics in annual tissues were derived from multiple in-season sampling of leaves and nuts for nutrients and biomass in all years with the most intensive sampling being conducted in 2009, 2010 and 2011. Trees in this orchard were 9 years old at the commencement of the experiment and 13 years old at completion, with an orchard level light interception of 78% in year 10, increasing to over 88% in year 13. In comparison with industry standards and midday photosynthetically active radiation (PAR) interception, yield in these orchards was very good from 2008 through 2011 while in 2012, for reasons that have not been determined, yields were very low. The majority of the data presented for nutrient dynamics in annual organs was derived from years 2009, 2010 and 2011 in which treatment differences were clearly evident, yields were representative and sampling was most intensive. Data of nutrient dynamics for perennial tissues was solely derived from the 2012 season when tree excavations and tree coring were also performed (task three, objective four). In these experiments the N treatment that was just adequate to achieve maximal yield in the majority of years was 275 lbs/ac; this treatment is considered the ‘best management’ treatment in these experiments (**Table 4a&b**).

Table 4a. Effect of UAN 32 and CAN 17 as N sources on kernel yield of Monterey almond with different N supply under fan jet and drip irrigations. Means not connected by the same letter within irrigation and same N rate are significantly different at * < 0.05, **< 0.1 and ns= non-significant.

Irrigation	Year	Nitrogen rate (lbs/ac)							
		125		200		**275**		350	
		UAN 32	CAN 17	UAN 32	CAN 17	**UAN 32**	**CAN 17**	UAN 32	CAN 17
Fan Jet	2011	2838	2942	3539	3290	**3674**	**3631**	3709	3497
				a	b				
		ns		*		**ns**		ns	
	2012	1747	1658	1979	1910	**2356**	**1973**	2270	2108
		ns		ns		**ns**		ns	
Drip	2011	3096	2580	3493	2974	**4289**	**3481**	4048	3886
		a	b	a	b	**a**	**b**		
		*		**		*****		ns	
	2012	1694	1786	1658	1827	**2071**	**1971**	2247	2157
		ns		ns		**ns**		ns	

Table 4b. Kernel yield (lbs/ac) of Nonpareil almond with different rates of N as UAN 32 under fan jet and drip irrigations. Means not connected by the same letter within irrigation are significantly different.

Irrigation	Year	Nitrogen rate (lbs/ac)				Probability
		125	200	275	350	
Fan Jet	2008	3069	3294	**3265**	3455	NS
	2009	2816	3066	**3217**	3304	0.0247
		b	ab	**a**	a	
	2010	2356	2885	**3511**	3277	0.0001
		c	b	**a**	a	
	2011	3871	4014	**4480**	4425	0.001
		b	b	**a**	a	
	2012	806	790	**884**	972	NS
Drip	2008	3506	3535	**3763**	3734	NS
	2009	2715	2944	**3184**	3489	0.0007
		c	bc	**b**	a	
	2010	2849	3413	**3735**	4030	0.0022
		c	b	**ab**	a	
	2011	3812	4275	**4644**	4736	0.0002
		c	b	**a**	a	
	2012	816	725	**858**	917	NS

Total N in leaves in mid summer in 2012 (low yield year) was 33lbs, 38lbs, 48lbs and 52lbs/ac for the four N application rates (125lbs, 200lbs, 275lbs and 350lbs/ac N) respectively. In contrast, total N in leaves at mid summer in 2011 (high yield year) was 19lbs, 25lbs, 31lbs, 35lbs/ac for the four N application rates (125lbs, 200lbs, 275lbs and 350lbs/ac N) respectively. The contents of P, K, S, Ca and Mg in 2011 in leaves for 275lbs/ac N rates were 1.5, 25, 1.7, 53 and 9lbs/ac and in 2012, when kernel yield was very low, leaf P, K, Ca and Mg contents for 275lbs/ac N rate were 2.7lbs, 34lbs, 94lbs and 14bs/ac respectively. Since nutrients present in leaves are either remobilized to perennial tissues or returned to soil as leaves senesce they do not, per se, contribute to nutrient demand. The timing of nutrient assimilation into leaves and the remobilization of nutrients from leaves will however alter the overall pattern of nutrient assimilation on a whole tree basis.

The annual N increment in perennial tree organs measured as the difference in whole tree standing nutrient content from December 2011 to December 2012, was 19, 37, 39 and 40 lbs/ac for the four N application rates (125lbs, 200lbs, 275lbs and 350lbs of N per acre) respectively. The annual increment in P, K, Ca and Mg was 7lbs, 34lbs, 3.1lbs and 2.5 lbs/ac under the N treatment that was just adequate to achieve maximal yield (275 lbs/ac in this experiment).Given the unusually low yields in 2012, it is probable that annual nutrient concentration in leaves and perennial tissues, and the total wood biomass produced was higher than would occur in a typical season. This is supported by the far greater than usual fruit nutrient concentrations observed in 2012 in contrast to any other season. This experiment will be repeated in 2013.

Annual nutrient export in harvested fruit was determined in all years of this experiment. In years 2009 through 2011 nitrogen in fruit at harvest represented >85% of whole tree nutrient fluxes. Total N export from the orchard in harvested crop is proportional to the total size of the crop and the nutrient concentration in that crop which varies in proportion to the ratio of fertilization rate to total annual N demand. In trees provided just adequate N to achieve maximal yield (275 lbs/ac in this experiment in years 2009-2011), each 1000lbs of kernel yield at harvest exported from the orchard 59 to 74lbs N while phosphorus and potassium export by 1000lbs kernel yield at harvest ranged from 7.5lbs to 9lbs and 65lbs to 85lbs respectively (**Table 5**). Mean S, Ca and Mg export by 1000lbs kernel yield was 2.3lbs, 7lbs and 4.5lbs respectively. The accumulation of micronutrients was also determined, but is not presented in this report. Fertilizer N application above or below the 275 lbs/ac rate altered N concentration in fruit and hence N export in fruit per 1000lbs kernel yield.

Table 5. Macronutrient export (lbs) in fruit by 1000lbs kernel yield in almond from 2008-2012 under fan jet irrigation. Means not connected by same letter within the same year are significantly different at *<0.05 and **<0.1. ns = not significant, T1= 125lbs N/acre, T2= 200lbs N/acre, T3= 275lbs N/acre and T4= 350lbs N/acre.

	2008				2009				2010				2011				2012			
	T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4
N	56	59	61	62	53	56	59	60	55	61	73	70	54	65	74	75	54	86	87	86
	c	bc	ab	a	b	ab	a	a	c	b	a	a	c	b	a	a	b	a	a	a
	*				*				*				*				*			
P	6.5	6.9	6.7	6.3	7.4	7.4	7.2	6.8	8.6	8.2	8.9	7.8	8.7	8.5	9	8.3	11	14	13	11
																	b	a	ab	b
	ns				ns				ns				ns				*			
K	53	54	54	52	74	72	73	71	88	81	80	82	77	76	78	75	91	100	87	88
									a	ab	b	ab								
	ns				ns				**				ns				ns			
S	2.3	2.4	2.4	2.5	2.1	2.2	2.2	2.2	2	2.2	2.5	2.4	2.4	2.7	2.9	3	2.4	3.5	3.1	3.1
									b	b	a	a	c	bc	ab	a	b	a	a	a
	ns				ns				*				*				*			
Ca	8.6	8.2	8.1	8.1	7.5	7.4	6.8	6.9	7.6	7.1	7.1	7.1	6.6	6.2	6	5.7	6.4	6.2	5.4	4.9
													a	b	bc	c				
	ns				ns				ns				*				ns			
Mg	4.8	4.7	4.7	4.7	4.5	4.5	4.4	4.3	4.6	4.4	4.6	4.4	4.6	4.4	4.5	4.4	5.1	5.5	5.0	4.7
	ns				ns				ns				ns				ns			

Sequential analysis of annual and perennial organs demonstrates that the majority of whole tree macro and micronutrient uptake occurs between anthesis and kernel fill with 30% of total N uptake occurring before 40 days after full bloom (DAFB) and 80-90% of the total N being accumulated by 130 DAFB coinciding with kernel filling. Data on whole tree nutrient demand and the in-season accumulation of nutrients in annual and perennial tissues can be used as a basis for managing fertilization in Almond.

This project also evaluated the effect of nitrogen and potassium rate and sources on almond yield and yield related parameters: fruit and kernel weight, number of fruits per tree and shelling percentage. Nitrogen rate had a significant yield effect in the second year (2009) of the experiment and persisted throughout the experiment. Increasing N supply increased yield up to 275lbs/ac, but there was no additional significant yield benefit above this rate. Source of N had no significant effect on Nonpareil yield response to N, but had significant effect on Monterey yield in 2011 only. K rate had no significant effect on yield of Nonpareil and had significant effect on Monterey yield in 2011, while K source also had significant effect on yield of Monterey in 2011 under drip irrigation (**Table 6**). Yield increase with increasing N application is attributed to an increase in number of fruits. There was no consistent effect of K supply and source on yield parameters of Nonpareil. There was a strong relationship between total yield and number of fruits per tree which increased with increasing N application. Shelling percentage is also positively correlated to kernel yield.

Table 6. Kernel yield of Monterey almond with different potassium fertilizer rates under fan jet and drip irrigations. Means not connected by the same letter within irrigation are significantly different at * < 0.05, **< 0.1 and ns= non significant.

Irrigation	Year	Potassium rate (lbs/ac)		
		100	200	300
Fan Jet	2011	3391	3674	3648
		b	a	a
		*		
	2012	2189	2344	2018
		ns		
Drip	2011	3565	4344	3989
		b	a	ab
		*		
	2012	2275	2082	2113
		ns		

Nutrient use efficiencies of nitrogen (N) and potassium (K) under differential fertilization rates and sources was also estimated in this project. Nitrogen use efficiency (NUE) calculated as N exported from the orchard in fruits and N accumulated in perennial tissues for growth over N applied in fertilizer and contributed by soil, ranged from 63% to 104% under sprinkler irrigation and 60% to 114% under drip irrigation for the N rate of 275lbs/ac in different years (**Table 7**). In these experiments an N rate of 275lbs/ac was the lowest N application rate that resulted in maximal productivity. NUE declined as N application rate increased. NUE was not affected by N sources. Potassium use efficiency (KUE) was highest for 100lbs/ac K application rate and declined as K application rate increase. Apparently, KUE exceeded 100% in most treatments and most years and increased with tree age for all K rate treatments. K sources only showed significant difference in KUE in 2010 where K application with SOP+KTS was higher than with other K sources. A KUE of over 100% for all K rates suggests that trees are accessing soil mineral reserves (**Table 8**).

Table 7. Nitrogen Use efficiency (%) of N sources UAN 32 and CAN 17. Letters indicate significant difference in NUE within the same year and irrigation at ** <0.1 level of significance and ns not significant.

Irrigation	Year	Nitrogen application (lbs /ac)							
		N 125		N 200		N 275		N 350	
		UAN 32	CAN 17	UAN 32	CAN 17	UAN 32	CAN 17	UAN 32	CAN 17
Fan Jet	2008	120	127	91	88	66	63	57	51
		ns		ns		ns		ns	
	2009	91	101	78	81	63	64	53	54
		ns		ns		ns		ns	
	2010	87	93	89	87	87	82	63	72
		ns		ns		ns		ns	
	2011	129	135	123	128	114	108	89	85
		b	a						
		0.0600**		ns		ns		ns	
Drip	2008	143	132	97	90	76	72	61	62
		ns		ns		ns		ns	
	2009	92	75	70	63	63	58	59	58
		a	b						
		0.0589**		ns		ns		ns	
	2010	105	78	94	81	97	92	90	86
		ns		ns		ns		ns	
	2011	125	142	120	129	113	110	102	101
				b	a				
		ns		0.0540**		ns		ns	

Table 8. Potassium use efficiency (K export in fruits + Perennial)/K applied) for K rates under fan jet and drip irrigation. Letters indicate significant difference in KUE within the same year and irrigation.

Irrigation	Year	Potassium applied (lbs/ac)			p value
		100	200	300	
Fan Jet	2008	189	101	71	<0.0001
		a	b	c	
	2009	269	133	97	<0.0001
		a	b	c	
	2010	294	156	105	<0.0001
		a	b	c	
	2011	320	190	126	<0.0001
		a	b	c	
Drip	2008	201	113	78	<0.0001
		a	b	c	
	2009	242	130	95	<0.0001
		a	b	b	
	2010	307	183	113	<0.0001
		a	b	c	
	2011	365	199	150	<0.0001
		a	b	c	

Fruit N accumulation increased until 163 days after full bloom [(DAFB) in all N rates (August 3rd, 2010)] and then declined slightly but not significantly. The sampling conducted here, at very close sampling intervals, confirmed that there is no increase in fruit N accumulation after 163 days corresponding to 100% hull split (August 3rd in 2010).

In 2011 a new task took place to improve our understanding of whole orchard nutrient balance. In this new task, researchers collected nutrient concentrations and biomass of all major organs of mature field grown almond trees by whole tree excavation, sequential tissue sampling and nutrient analysis in trees grown under four nitrogen rate treatments. The amount of nutrient accumulated in perennial organs over one year (2012) was determined as the difference between the total tree nutrient pool in dormant trees prior to, and at the completion of a single season (**Figure 4**). The dynamics of nutrient remobilization in perennial tissues during early season growth and the accumulation of nutrients in perennial tissues were determined by sequential coring, tissue sampling, biomass estimation and whole tree excavation. Nutrient resorption from leaves was determined from multiple seasonal leaf samples. All measurements were replicated in trees of differing N fertilization regimes. In 2013 more data have been collected and sent to the laboratory for their nutrient content analysis to support the results obtained in 2012. Data collected in 2012 were analyzed from January 2013 to July 2013 and some key results are presented as follow.

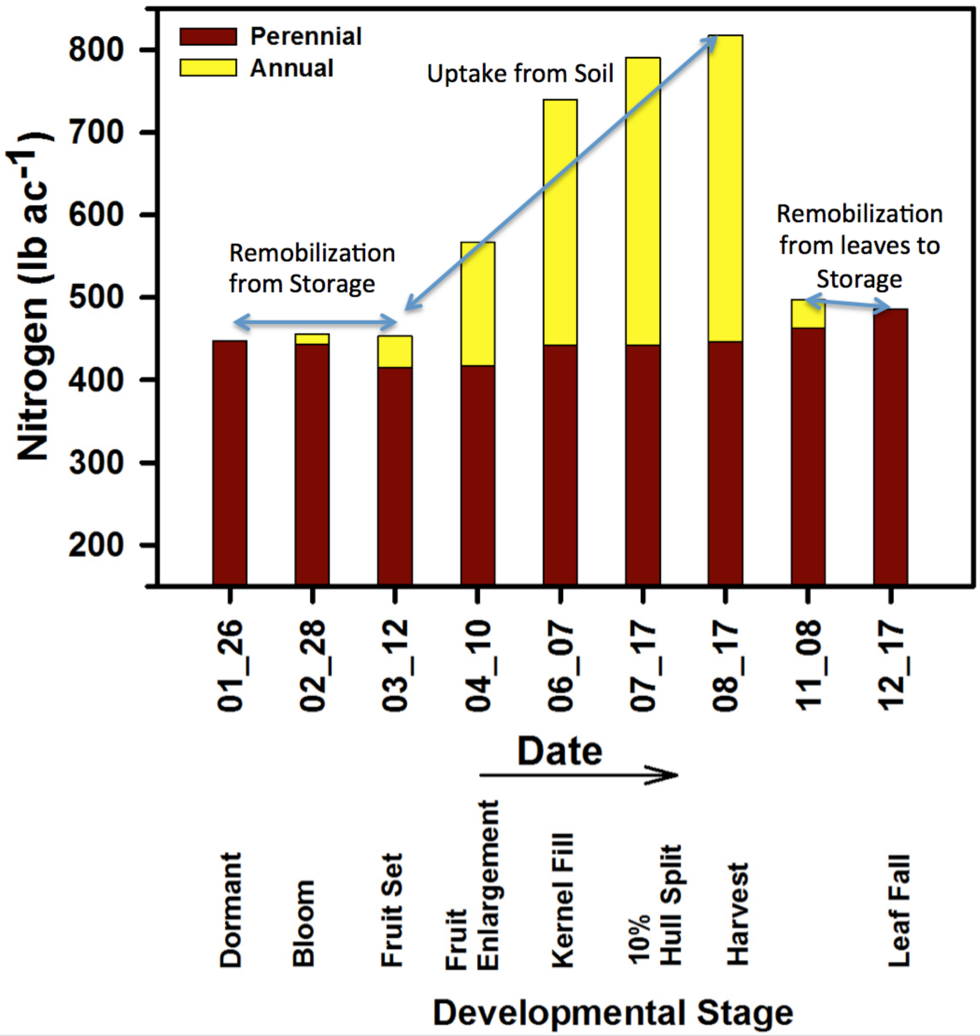

Figure 4. Nitrogen partitioning in perennial and annual organs of mature almond trees. The accumulation in perennial biomass is the total N accumulated in the trees from planting to the age of 13 years.

While it is not possible to distinguish nutrients accumulated in the previous year and remobilized from nutrients acquired in the current year, it can be presumed that the decline in the nutrient content of perennial organs in the early spring and the equivalent increase in nutrients in annual organs is a measure of the remobilization of the stored nutrients for flowering, fruit set and early fruit growth and initial leaf expansion. This pool is referred to here as stored N. Nitrogen contents in whole tree perennial biomass declined during anthesis and reached the lowest content when fruit set and completion of leaf out occurred. Total perennial biomass N content and seasonal fluxes were strongly influenced by N application rate. N concentration in perennial organs was lowest for 125lbs/ac N rate and increased with N application up to 275lbs/ac N, but did not increase further. The most variable pool of N was roots <1cm diameter.

The size of the whole tree remobilized N pool increased with increasing N application and was maximal at 49lbs/ac for 350lbs/ac N application. The pool of remobilized P, K, S and B for 275lbs/ac N application rate was 7lbs/ac, 27lbs/ac, 1.72lbs/ac, and 0.53lbs/ac respectively.

Trends in nutrient contents through the year demonstrate that N was stored predominantly in roots >1cm diameter as well as in canopy branches, while P was stored mostly in roots >1cm diameter and in canopy branches and branches <2.5cm diameter. K storage was greatest in canopy branches followed by branches <2.5cm diameter and roots >1cm diameter. The major storage site for S were branches <2.5cm diameter and roots >1cm diameter, while B was stored in canopy branches and roots >1cm diameter

Recent Publications & Outreach Activities:
This research has been adopted by the Almond Board of California as the new standard for nutrient management and is being widely publicized and distributed. This research project has been presented at grower, industry, extension, CDFA, ASA and university venues including keynote presentation at The Almond Conference. A webpage summarizing this work has been posted on the Almond Board's main grower information portal at http://www.almondboard.com/Growers/OrchardManagement/PlantNutrition/Pages/Default.aspx and on the University of California Fruit and Nuts Website http://ucanr.edu/sites/scri/Crop_Nutrient_Status_and_Demand__Patrick_Brown/ and is in process of being included in the California Almond Sustainability Program online system. This work has been published in *Pacific Nut Producer* and other industry publications. A Google search for "nutrient management in almond" yields 20 top ranked pages based upon this research.

Publications:

Alsina, M.M., A.C Borges, and D.R. Smart. 2013. Spatiotemporal variation of event related N2O and CH4 emissions during fertigation in a California almond orchard. Ecosphere.

Sanden, B, P.H. Brown, R. Snyder. 2012. New insights on water management in almonds. "Regulatory Issues Impacting California Agriculture" Visalia, California 7-8 Feb, 2012 Proceedings: Amer. Soc. Agron. Calif. Chap. pp. 88-93. Univ. Calf. Davis, http://calasa.ucdavis.edu

Schellenberg D.L., M.M. Alsina, S. Muhammad, C.M. Stockert, M.W. Wolff, B.L. Sanden, P.H. Brown and D.R. Smart. 2012. Yield-scaled global warming potential from N2O emissions and CH4 oxidation for almond irrigated with N fertilizers on arid land. Agriculture, Ecosystems and Environment 155: 7-15.

Shackel K.A., T.L. Prichard, L.J. Schwankl. 2012. Irrigation scheduling and tree stress. In: Prune production manual, University of California, ANR publication #3507.

Valdez Zarate, J.L., M.L. Whiting, B.D. Lampinen, S. Metcalf, S.L. Ustin, and P.H. Brown. 2012. Prediction of leaf area index in almonds by vegetation indexes. Computers and Electronics in Agriculture. 85:24-32.

Presentations:

Brown, P. 2012. Nutrient Management of Almonds. Almond Board of California: Sacramento CA.1800 atten.

Brown, P. 2011. Update on Nutrient Management of Almonds. Almond Board of California: Modesto CA.1800 atten.

Brown, P. 2011. CDFA-FREP Annual Conference. Management of N in Tree Crops. Paso Robles CA. 300 atten.

Brown, P. 2011. Sampling strategies for Nutrient Management in Tree Crops. Fluid Fertilizer Foundation Meeting. Stockton CA. 55 atten.

Brown, P. 2011. Stakeholder Meeting Paramount Farming: Bakersfield CA. 18 atten.

Brown, P. 2012. Foliar fertilization of tree crops. ASHS. Miami FL. 60 Attendees.

Brown, P. 2012. Management of N in Almonds. CDFA-FREP and WPHA Annual Workshop. Modesto CA. 400 atten. Expert Panel Member presentation and discussion.

Brown, P. 2012. Managing large scale collaborative research projects. Pomology Extension Continuing Conference. Davis CA. 50 atten.

Brown, P. 2012. Nutrient Budget and development of new sampling strategies for N management. Northern San Joaquin Almond Day. Merced, CA. 420 atten.

Brown, P. 2012. Nutrient Budget and development of new sampling strategies for N management. ISHS Meeting on Nutrition of Tree Crops, Chakrabourty Thailand. 250 atten.

Brown, P. 2012. Nutrient Budget and development of new sampling strategies for N management. Australian Almond Industry Annual Meeting, Nuriootpa, SA. 220 atten.

Brown, P. 2012. Plant Nutrition in a Changing Environment. German Soc. for Plant Nutrition. 200 atten.

Brown, P. USDA Grant Review SCRI CAP Project Panel, Washington DC.

Chabrillat, S. et al. 2012. Quantitative mapping of surface soil moisture with hyper spectral imagery using the HYSOMA interface. IEEE International Geoscience and Remote Sensing Symposium. Munich, Germany.

Sanden, B. 2012. “Irrigation Management to Maximize Almond Production in the SJV”, Organic Almond Farming Workshop, Selma CA. 64 atten.

Sanden, B. 2012. Kern almond meeting, irrigation management and workshop. Kern Soil and Water Newsletter.

Sanden, B. et al. 2012. Almond Worlbsroup Tour, Kern County.

Sanden, B. et al. 2012. California’s Effort to Improve Almond Orchard Kc. European Geosciences Union General Assembly. Vienna, Austria.

Schellenberg D. et al. 2012. Gross N transformations and 15N assimilation after arid land fertilization at the tree scale. ESA. Portland OR.

Shackel K., Sanden B. 2011. Fertigation: Interaction of Water and Nutrient Management in Almonds. Almond board of California annual report #09-HORT11.

Saa. S. 36th Annual Nickels Field Day Meeting. 2013. Speaker. 60 atten

The Seventh International Symposium on Mineral Nutrition of Fruit Crops. Thailand. 2012. Speaker. 400 atten

Saa, S. American Society of Agronomy: Plant & Soil Conference. 2012. Speaker. 250 atten.

Saa, S. Almond Board of California Conference. 2012. Speaker. 1800 atten.

Saa, S. 35th Annual Nickels Field Day Meeting. 2012. Speaker. 60 atten.

Field Meeting Almond Irrigation & Nutrient Management for High Yield. Year: 2011. Speaker. 150 atten

Saa, S. Laboratory Analysis Workshop. 2011. Speaker. 40 atten.

Saa Sebastian, Muhammad Saiful, Castro Sebastian, Brown Patrick; Effect of Spur Type, Foliar Sprays, and Differential Nitrogen Rates on Leaf Nutrient Content and Spur Leaf Area of Almond Trees. Thailand; International ISHS Symposium on Mineral Nutrition of Fruit Crops. 2012.

<u>Posters:</u>

Saa Sebastian, Muhammad Saiful, Brown Patrick; Development of leaf sampling methods and nutrient-budget fertilization; Almond Board of California, Modesto, USA. 2011. Poster.

Patrick Brown, Saiful Muhammad, Sebastian Saa Silva and Eike Luedeling; Development of Leaf Sampling Methods and Nutrient-budget fertilization; Almond Board of California, Modesto, USA. 2010. Poster.

Patrick Brown, Sebastian Saa Silva, Kenneth Shackel, Michael Whiting, Theodore Sammis, Bruce Lampinen, David Slaughter; Advanced Sensing and Management Technologies to Optimize Resource Use in Perennial Crops: Nutrient and Water Status ASHS Palm Springs, California, USA. 2010. Poster.

Saa Sebastian, Muhammad Saiful, Brown Patrick; Development of leaf sampling and interpretation methods Almond Board of California, Modesto, USA. 2010. Poster.

Brown Patrick, Eike Luedeling, Sebastian Saa, Jeremy Nunez; Development of leaf sampling and interpretation methods for Almond; International Plant Nutrition Conference, Sacramento, USA. 2009. Poster.

Patrick Brown, Saiful Muhammad, Sebastian Saa, Eike Luedeling; Development of Leaf Sampling Methods and Nutrient-Budget Fertilization. International Plant Nutrition Conference, Sacramento, USA. 2009. Poster.