Development and Testing of a Mobile Platform for Measuring Canopy Light Interception and Water Stress in Almond

Project No.: **09-HORT13-Lampinen**

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Objectives:

Data collected by the authors over the past several years has provided a rough upper limit to productivity in walnut and almond based on the percentage of the available midday canopy photosynthetically active radiation (PAR) that is intercepted and the age of trees. However, most of the data that was collected previously had limitations. The methods of measuring percent PAR interception using a handheld lightbar (Decagon Devices, Pullman, WA 99163) were relatively slow and labor intensive. For this reason, much of the lightbar data that was used to develop the relationship was based on sampling of relatively small samples of trees. Often the area for the yield and PAR interception data did not match (i.e. PAR data from 5 trees and yield data from either one tree or from an entire row). We have recently outfitted a Kawasaki Mule with a light bar that is able to measure light across an entire row (up to 28 feet wide). The data can be stored on a datalogger at intervals of less than 1 foot down the row at a travel speed of about 4.5 mph giving us a much better spatial resolution in much less time than was possible in the past.

Preliminary results suggest that measuring leaf temperature using an IR spot sensor or 2D imagery while accounting for windspeed, leaf orientation, and incident PAR can provide a potential means of detecting plant water status. Ondimu (2007) found that a combination of a thermal image with a red-green-blue (RGB) color image was able to account for moss temperature, texture and color, as well as predict water stress. We plan to use a sensor fusion technique to detect plant water stress in which we will look at the leaf temperature using an infra-red (IR) sensor, incident PAR using our PAR measurement system, color image (RGB) for leaf inclination information, and a wind speed sensor.

Objective 1. The first aspect of this proposal involves updating and retrofitting the Mule (**Figure 1**) with sensors designed to develop the ability to detect water stress in trees.

Objective 2. The second component of this proposal involves using the Mule mounted lightbar setup to measure light interception and corresponding yield in almond orchards throughout the almond growing area of California. The goal of this aspect of the work is to help establish the upper limit to the light interception/yield relationship for almond (shown in **Figure 4**).

These data are of use for any studies that aim to quantify the impact of treatments on yield. By measuring canopy light interception on a large scale, the impacts of differences in canopy development can be separated out from other treatment impacts allowing much more robust data interpretation.

Interpretive Summary:

A mobile platform has been developed that can map orchard light interception. Preliminary data has also been collected with a portable sensor suite consisting of an infrared thermometer and sensors for relevant ambient conditions. This sensor suite was used to measure leaf temperature, light intensity, air temperature, air humidity, and wind speed in almond trees with different levels of stem water potential. Preliminary results suggest that this technology has promise for evaluating plant water stress under field conditions. Adapting this sensor suite to the mobile platform presents some challenges.

The mobile platform was used extensively for mapping midday canopy light interception in almond orchards. Data collected with the mobile platform suggests that there are a number of potential uses for this technology. The first is for providing a baseline for assessing how an orchard is performing relative to other orchards of similar age and variety. Another is for separating out the effects of rate of canopy growth from productivity per unit canopy light intercepted in different clones or varieties. A third potential use if for assessing the efficacy of different fumigants by again separating out the effects of canopy size from productivity per unit light intercepted. A fourth use is for evaluating the impacts of different pruning regimes on canopy growth, light interception and productivity per unit light intercepted. This technology also allows the elimination of canopy size differences from any type of trial.

Materials and Methods:

Objective 1. Mule platform modification - The existing Mule mounted lightbar setup has been modified in order to make it more robust. This included removing the cable support system and replacing them with supports underneath as well as adding a protective bumper to push low hanging branches up and over the lightbar (**Figure 1**). A sub-meter global positioning satellite (GPS) receiver and radar were added to provide accurate positional information. In addition, two infrared thermometers were added for measuring soil surface temperature under the tree canopy and in the middle of the drive row.

Additional work under this objective was performed using a handheld sensor suite for the preliminary investigation for the ability to detect stress using the mobile platform.

To study the relationship between leaf temperature and plant water status, we have developed a sensor suite to measure leaf temperature and relevant microclimate information. The sensor suite consists of an infrared thermometer (4000.4ZL, Everest Interscience, Tucson, AZ), a quantum sensor (LI-190, LICOR inc., Lincoln, NE), an anemometer (VelociCalc 8360, TSI Inc., Shoreview, MN) and air temperature and relative humidity probe (HMP35C, Visalia Inc., Woburn, MA) interfaced to a CR3000 datalogger (Campbell Scientific Inc., Logan, UT).

The sensor suite was used in a 19 year old almond orchard (variety Nonpareil) located near Arbuckle, California. Measurements were taken at two different times of day. **Table 1** lists the range of water potentials and ambient conditions during field measurements. For each tree, temperatures of both sunlit and shaded leaves were measured using the infrared thermometer. Air temperature, relative humidity, and wind

Figure 1. Current design of Kawasaki Mule mounted lightbar after summer 2009 modifications showing adjustable end section and branch bumper on front designed to aid in pushing through orchards with many low overhanging branches.

speed were measured in the vicinity of the target leaf at the time of leaf temperature measurement. Light intensity was measured immediately after each temperature measurement using a quantum sensor oriented to the same angle as the leaf surface to the sun. To minimize transient effects, temperature measurements were taken only when the sky was not overcast and wind was still or calm.

Table 1. Experimental dates and range of parameters.

Variety	Date	Trees	Range			
			Water potential (MPa)	Air temperature (°C)	*VPD* (kPa)	Wind speed (m/s)
Nonpareil	7/21/09	26	-4.60 to -0.72	29.2 to 34.3	2.3 to 3.6	0.1 to 1.4
Nonpareil	8/3/09	36	-3.96 to -0.93	24.9 to 29.4	1.6 to 2.6	0.1 to 1.8

A pressure chamber (3005-Series, Soilmoisture Equipment Corp., Santa Barbara, CA) was used to measure stem water potential (SWP) from shaded interior leaves that were wrapped with foil-covered plastic bags at least 15 minutes before the measurements to prevent the leaves from transpiring so that their water potential can equilibrate with the stem water potential. The stem water potential measurement was taken within 10 minutes of sensor suite measurements.

Objective 2. Refine light interception/yield relationship in almond. Nineteen almond orchard sites of varying ages and varieties from throughout the almond growing area of California were selected for measurements (**Table 2**). An emphasis was placed on orchards with Nonpareil but other varieties were also included. Light bar measurements were done in 10-20 rows (depending on orchard size and variability) in representative areas of the orchard during June to August. A portable weather station with temperature, relative humidity and photosynthetically active radiation sensors was set up outside of each orchard to provide reference data (on a one minute basis) during the time measurements were being taken. The photosynthetically active radiation (PAR) data from this station was used to calibrate the sensors on the Mule lightbar throughout the measurement period. The data rows were then flagged and at harvest time, rough field weights were taken from the Nonpareil or other primary variety in the orchards. Subsamples from each variety were taken and dried and shelled to estimate kernel yield. In some cases measurements were done in orchards that are being used for other almond trials including sites from the USDA Area Wide methyl bromide alternatives trials as well as projects funded under a USDA Specialty Crop Research Initiative (SCRI) grant. Other orchards were mapped from rootstock and pruning and training trials. Utilizing orchards from other studies allows us to utilize the data for multiple purposes.

Table 2. Orchards sites mapped with Mule lightbar during 2009 season.

Site #	County	Trial	Date mapped
1	Butte	Orchard removal	09/01/09
2	Colusa	SCRI- Arbuckle	06/18/09
3	Colusa	Nickels almond rootstock	07/31/09
4	Colusa	Nickels organic almond	07/30/09
5	Colusa	Nickels almond pruning/training trial	0730/09
6	Colusa	Shackel almond deficit trial	06/19/09, 06/24/09
7	Glenn	Almond light interception/yield	06/22/09
8	Glenn	Orchard removal	09/20/09
9	Kern	Billing Variety Trial	07/19/09, 07/20/09
10	Kern	SCRI- Belridge	07/21/09
11	Kern	Spur Dynamics	07/03/09, 07/04/09
12	Madera	Holtz almond surround trial	06/16/09, 06/17/09
13	Madera	Methyl bromide grower south orchard replant site	07/02/09
14	Madera	Paramount New Columbia fumigation/irrigation trial	06/30/09
15	Madera	Paramount New Columbia main fumigation trial	07/22/09
16	Sutter	DeJong almond model site	10/06/09
17	Stanislaus	SRCI- Salida	08/19/09
18	Stanislaus	Duncan almond pruning, spacing and training trial	08/12/09
19	Stanislaus	Duncan almond rootstock	08/17/09

Results and Discussion:

<u>Objective 1.</u> Experimental data were randomly split into calibration and validation sets. The calibration set consisted of approximately 60% of the data and the validation set consisted of the remaining 40%. Using a multiple linear regression technique that utilized a stepwise model selection procedure, empirical prediction equations for temperature of the leaf minus the temperature of the air ($T_L - T_a$) were developed and are presented in **Table 3**. Independent parameters were stem water potential, light interception, wind speed, and air vapor pressure deficit. All parameters except wind speed were significant. The lack of significance of wind speed might be due to calm wind conditions that prevailed during the experiments. The R^2 value for the calibration data was 0.71 (equation 5).

Figure 2 shows the comparison between predicted and measured ($T_L - T_a$) for the calibration set (**Figure 2a**) and the validation sets (**Figure 2b**). The measured versus predicted data for the calibration as well as prediction data sets shown in these figures not only resulted in high R^2 values, but the slope and intercept values for these plots were close to 1 and 0, respectively indicating models with good predictive ability. When

Table 3. Empirical prediction models developed by the calibration data sets and the R^2 values corresponding to both calibration and validation data sets

Variety	Empirical prediction model	R^2 value		
		Calibration set	Validation set	
Nonpareil	$Y = 2.83648 - 0.00164\, X_1 \cdot X_2 - 1.23827\, X_3$	0.714	0.758	(1)

Note: Y = ($T_L - T_a$) [°C]
X_1 = stem water potential [MPa]
X_2 = photosynthetically active radiation [□mol s^{-1} m-^{2}]
X_3 = air vapor pressure deficit [kPa]
X_4 = wind speed [m s^{-1}]

the calibration equations were used on the prediction data set, high R^2 value of 0.76. These results are very promising and indicate that the sensor suite could be used to determine plant water status.

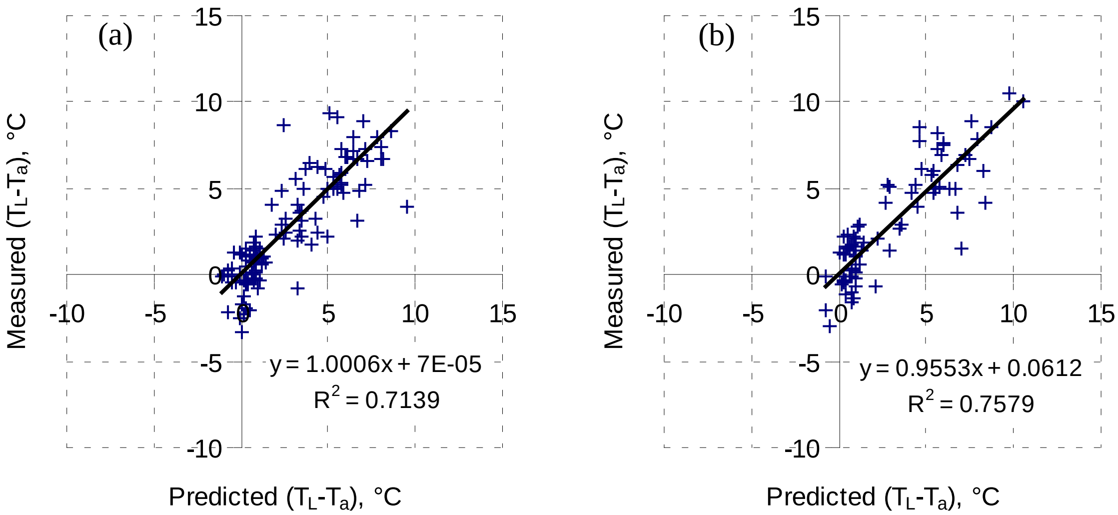

Figure 2. Plots of predicted vs. measured ($T_L - T_a$) for almonds using both datasets obtained on 7/21/09 and 8/3/09. Sixty percent of all data were split into (a) calibration set to develop a prediction model (equation 5) and the rest of data were used as (b) validation set to validate the model.

Since stem water potential represents overall plant water status, it may be better to measure temperature and ambient conditions in the vicinity of multiple leaves on a tree and use the average values for leaves in similar lighting conditions to determine plant water status. Fortunately, data obtained on 8/3/09 consisted of 2 to 3 sets of measurements per tree under similar lighting conditions (i.e., 2 to 3 sunlit and 2 to 3 shaded leaves were measured). Use of average values corresponding to leaves under similar conditions, resulted in improvement in R^2 values from 0.76 to 0.83 (**Figures 3a** and **3b**). This is very encouraging and we plan to further explore this possibility during the 2010 growing season.

It should be noted that our ultimate interest is to predict plant water status using the data obtained from various sensors included in the sensor suite. This requires the prediction of stem water potential using the temperature differential between the leaf and its surrounding environment. Often indices such as crop water stress index (CWSI) (Idso et al., 1981; Jackson et al., 1981; Jackson et al., 1988) are used to indicate plant water status. We are currently exploring these possibilities.

Table 4. Empirical prediction models for the data sets that have multiple data under similar lighting conditions on the same tree. Models were developed using individual measurements and the average data.

Var.	Date	Data used	Empirical prediction model	R^2 value	
Nonpar.	8/3/09	Individual	$Y = 0.31720 - 0.00192\, X_1 \cdot X_2 + 0.00023\, X_1 \cdot X_2 \cdot X_3 \cdot X_4$	0.7556	(2)
		Average	$Y = 0.17118 - 0.00207\, X_1 \cdot X_2 + 0.00031\, X_1 \cdot X_2 \cdot X_3 \cdot X_4$	0.8332	(3)

Note: $Y = (T_L - T_a)$ [°C]
X_1 = stem water potential [MPa]
X_2 = photosynthetically active radiation [□mol s^{-1} m^{-2}]
X_3 = air vapor pressure deficit [kPa]
X_4 = wind speed [m s^{-1}]

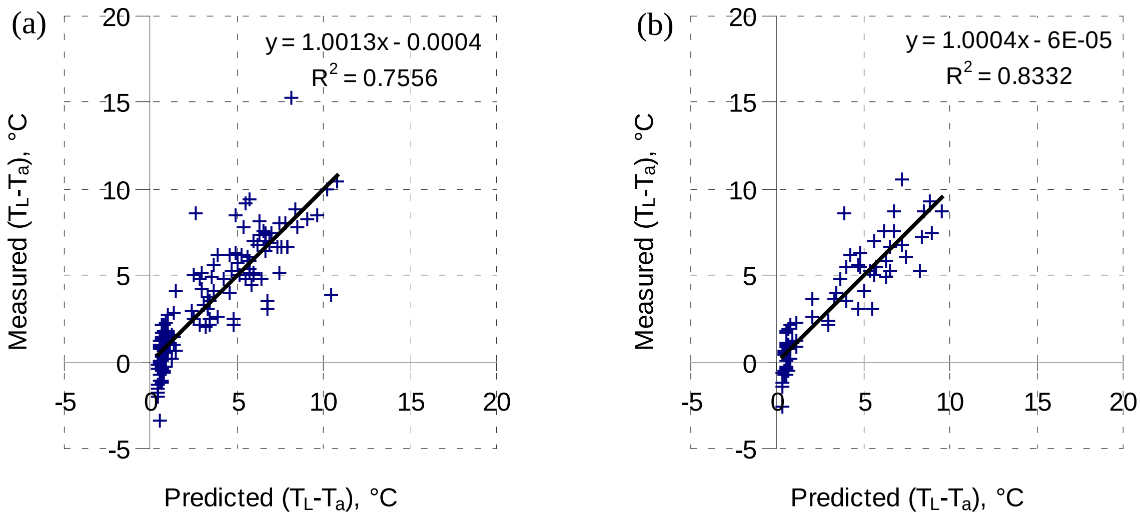

Figure 1. Plots of predicted vs. measured leaf−air temperature ($T_L - T_a$) for almonds to show effect of using average data. The model was developed using 8/3/09 dataset that represents (a) individual measurements, and (b) averaged data from the same lighting conditions and same tree.

Objective 2. Data for light interception and yield will be used to refine the relationship shown on the graph shown in **Figure 4**. Because the data in **Figure 4** was collected with a hand lightbar and the yield and light interception areas were not always equal, there is quite a bit of variability in the data. With a better estimate of the maximum productivity per unit light intercepted that can be obtained with harvesting equal areas to those measured with the Mule light bar, these data can be used to assess potential orchard yield and will allow us to separate out canopy light interception as a variable in other research projects. For example, if a pruning study is being conducted, this tool will allow the separation of the effect of the pruning treatment on overall canopy light interception as opposed to the effect of the pruning treatment on productivity per unit canopy. It will also allow block to block variability to be assessed before or after a research trial is initiated. These data will also allow us to look at how much of the

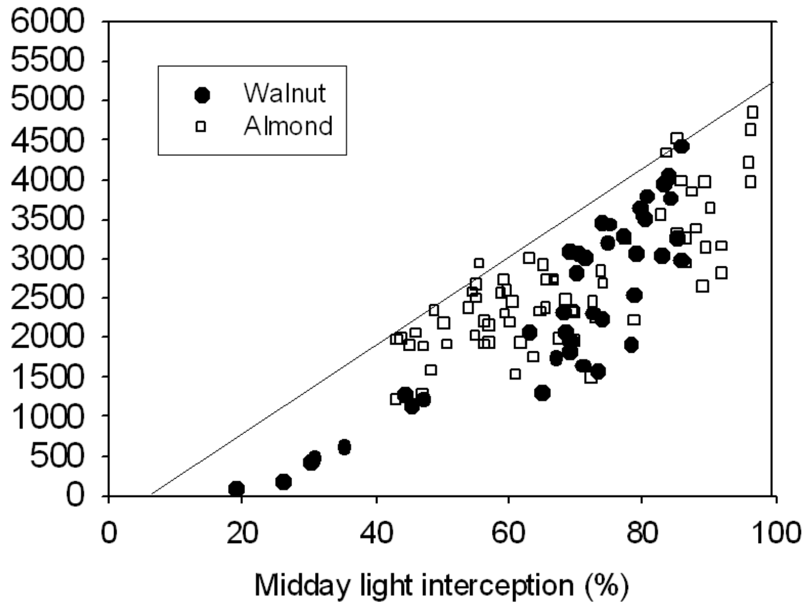

Figure 4. Midday canopy light interception versus yield relationship from various almond and walnut trials from throughout state using hand lightbar.

variability in yields across an individual orchard is due to differences in canopy light interception as compared to other factors. These data can also be used to evaluate productivity of new almond selections compared to existing cultivars. Finally, these data will allow any orchard to be evaluated as to how well it is producing compared to other orchards of similar canopy cover. This will allow a grower to assess how current management practices are impacting productivity per unit canopy.

Data collected during the 2009 season with the Mule lightbar from the 19 orchards listed in **Table 1** is shown in **Figure 5**. It appears that a fair number of orchards produced higher yields than we saw previously (**Figure 4).** This may be due to a number of factors. First, the orchards used for study in 2009 were selected based on farm advisor recommendations for some of the most productive orchards in their counties since we were looking for upper limits to the light interception and productivity relationship. A second factor is the possibility that some of these high yields are due to alternate bearing effects. An orchard with a low yield one year due to frost, poor bloom time weather, etc. can have a higher yield the following year. These same orchards are being followed in 2010 to see if alternate bearing was a factor in these high yields. A third possible contributing factor is tree height effects. If one variety is taller than the neighboring varieties, a percentage of yield can be shifted a shorter variety to a taller variety due to increased light interception for the tall variety over the course of the day.

The data collected with the mobile lightbar has many potential uses. One use is to look at the productivity of different cultivars or varieties as a function of both canopy size and

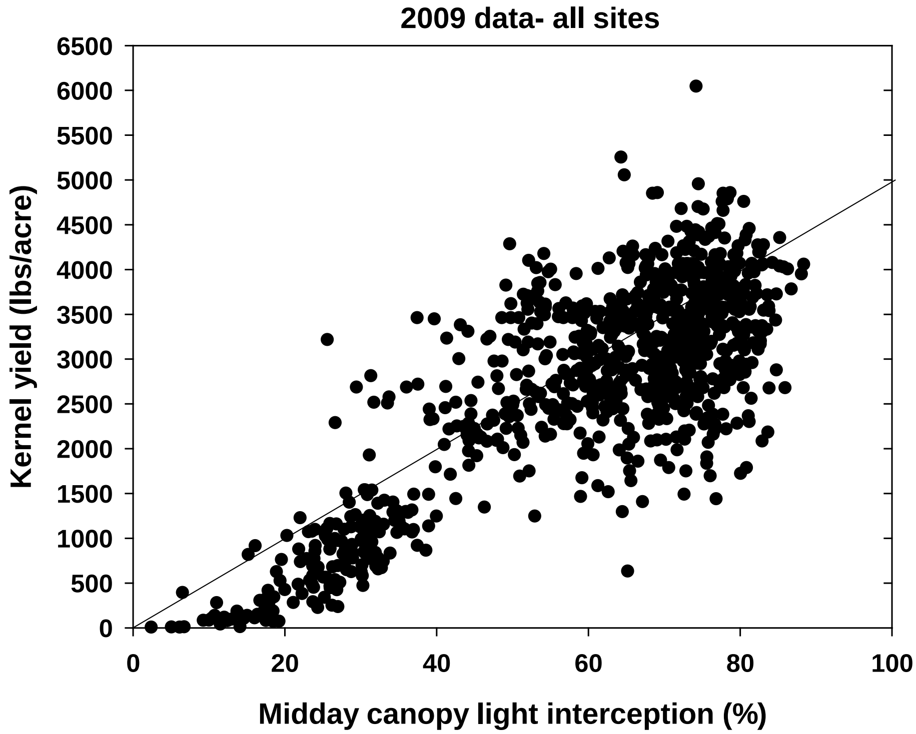

Figure 5. Midday canopy light interception versus yield relationship from mobile platform data for almond sites throughout state for 2009 season.

productivity per unit light intercepted. We have not previously been able to separate out these two factors. **Table 5** shows the yield, light interception and yield per unit light intercepted for the different Nonpareil sources as well as the varieties included in a

Table 5. Midday canopy light interception, kernel yield and yield per unit light intercepted by Nonpareil source and variety for McFarland Variety trial 2009.

Variety	Midday canopy PAR interception (%)	Yield (kernel pounds/acre)	Yield per unit PAR intercepted
Nonpareil-J	57.1 a	3512.8 bc	63.4 cd
Nonpareil- 38270	54.1 a	3798.5 a	71.8 bc
Nonpareil- Newell	53.9 a	4004.2 a	72.8 abc
Nonpareil- Nico	53.3 a	3850.7 a	69.3 bc
Nonpareil- 6	52.9 a	3660.6 bc	68.9 bc
Nonpareil- 5	52.5 a	3476.2 bc	72.0 bc
Nonpareil- DR	51.5 a	3976.6 a	76.1 abc
Sweetheart	50.7 a	2906.4 d	69.6 bc
Selection 2-19E	45.7 bc	3284.8 c	71.6 bc
Chips	44.0 c	2558.7 de	55.9 d
Kochi	43.5 c	2259.0 e	52.6 d
Winters	35.9 d	2415.1 e	63.9 cd
Kahl	33.4 d	2558.7 de	85.2 a
Marcona	33.0 d	2561.9 de	77.7 ab

variety block near McFarland, CA. These data suggest that there is no difference in productivity per unit light intercepted among all of the Nonpareil sources but there was a significant difference in yield (**Table 5**). This may be due to alternate bearing effects- the data for the 2010 season should help clarify this issue. In addition, some varieties produced fewer kernel pounds per unit light intercepted suggesting there may be differences efficiency of production for different varieties. Data for multiple years will be needed to differentiate yield efficiency

Another potential use of these data is to look at the effects of different fumigation treatments on productivity based on separating out canopy size effects from effects of productivity per unit light intercepted. An example of this is shown in **Table 6**. It is clear from these data that different fumigants can both have an effect on yield by influencing canopy size but also by influencing productivity per unit canopy light intercepted. This can be seen in the methyl bromide treatments that led to both smaller tree size and less productivity per unit light intercepted. It is possible that this is actually a pruning effect since growers tend to prune smaller trees more vigorously.

Table 6. Midday canopy light interception, kernel yield and yield per unit light intercepted by fumigation treatment and coverage, Madera County methyl bromide alternatives site 2009.

Fumigant, lbs per treated area	Treated area in tree row (and % of orchard area treated)	Fumigant per orchard acre (lbs)	2009 Midday canopy light interc. (%)	2009 Yield (kernel lbs/acre)	2009 yield per unit light intercepted
Control	8-ft strip (38%)	0	12.2 e	161 d	12.1 c
MB, 400	8-ft strip (38%)	152	15.1 de	455 cd	25.7 b
Telone II, 350	8-ft strip (38%)	133	17.7 cd	547 bc	28.6 b
CP, 400	8-ft strip (38%)	152	24.3 ab	932 a	38.2 ab
CP, 300	8-ft strip (38%)	114	23.5 ab	975 a	42.2 a
CP, 200	8-ft strip (38%)	76	26.8 a	979 a	37.2 ab
CP, 400	8x8-ft tree sites (17%)	68	24.3 ab	811 ab	36.9 ab
IM:CP 50:50, 300	8-ft strip (38%)	152	25.6 ab	948 a	37.4 ab
Telone C35, 550	8-ft strip (38%)	209	24.4 ab	905 ab	37.1 ab
Telone C35, 550	8x8-ft tree site (17%)	93	21.6 bc	778 abc	36.1 ab
Telone C35, 550	Broadcast (100%)	550	25.5 ab	941 a	36.6 ab
Pic-clor 60, 550	8-ft strip (38%)	209	26.3 ab	1123 a	43.2 a
Pic-clor 60, 551	8-ft strip (38%)	152	25.7 ab	834 ab	32.5 ab

MB = Methyl Bromide
CP = Chloropicrin
IM = Iodomethane
Pic-clor = Chloropicrin

Preliminary Conclusions:

A portable sensor suite consisting of an infrared thermometer and sensors for relevant ambient conditions was developed and used to measure leaf temperature, light intensity, air temperature, air humidity, and wind speed in almonds with different levels of stem water potential. Empirical models were developed for the temperature differential between the leaf and surrounding air as a function of stem water potential, light intensity, vapor pressure deficit, and wind speed. These empirical relationships resulted in high R^2 values in the range of 0.70 and 0.71. In addition, we found that use of average data for multiple leaves under similar lighting conditions (sunlit or shaded) results in an improvement in R^2 value indicating that it is better to use average values of temperatures and associated ambient conditions of similarly lit leaves to improve the model.

Data on midday canopy light interception collected with the modified mobile platform suggests that there are a number of potential uses for this technology. The first is for providing a baseline for assessing how an orchard is performing relative to other orchards of similar age and variety. Another is for separating out the effects of rate of canopy growth from productivity per unit canopy light intercepted in different clones or varieties. A third potential use if for assessing the efficacy of different fumigants by again separating out the effects of canopy size from productivity per unit light intercepted. Additional investigations using this technology include looking at the effect of tree spacing and orchard age on productivity per unit light intercepted. This technology also allows the elimination of canopy size differences from any type of research trial.

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