REFINING THE RELATIONSHIP BETWEEN CANOPY LIGHT INTERCEPTION AND YIELD IN WALNUT

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ABSTRACT

The existing mobile platform light bar was redesigned in order to make it more robust and adjustable to a wider range of tree spacing. In addition, more accurate soil temperature sensors were added. This second generation mobile platform light bar was used during the 2011-2013 seasons and performed well. In addition to the second generation mobile platform light bar, a new harvest supercart equipped with GPS, continuous yield monitoring capability, self-contained hydraulics and an auto-sampler were also built with partial funding from this project. Light measurements continued on a large number of walnut orchards of varying ages and tree densities. An upper limit of about 0.05 in-shell tons per acre for every one percent of light that can be intercepted has continued to be supported. When all of the walnut data from the last five years was combined, it was found that midday canopy light interception increased with orchard age until about 10-12 years when it tended to flatten and approach a value of near 93 percent. This results in a mature walnut orchard yield potential above 4 tons per acre. Work was continued on the canopy sensor suite for assessing plant water status. The results were promising and suggest the possibility of further developing this classification technique to assess plant water stress for irrigation scheduling in walnut orchards. This has resulted in the development of a continuous leaf monitor (for shaded leaves) that can be connected to the internet via the cell phone network providing real time information for aiding in irrigation scheduling

PROBLEM AND ITS SIGNIFICANCE

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. However, most of the data that was collected previously had limitations. The methods of measuring percent PAR interception using a handheld light bar (Decagon Devices, Pullman, WA 99163) were relatively slow and labor intensive. For this reason, much of the light bar 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). In the 2009 and 2010 seasons, we began using the first generation light bar for automated measurement of canopy PAR interception. In the winter of 2011, we completed the second generation light bar (adjustable from 8-32 feet) which was mounted on the Kawasaki Mule in the spring of 2011 and used during the 2011-2014 summer seasons.

The data generated with the mobile platform light bar are useful 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 more robust data interpretation.

A pressure chamber is often used to measure stem water potential of a plant to determine plant water status. However, measuring plant water status using a pressure chamber is tedious and time consuming, and is not suitable for measuring plant water status of a large number of trees making it expensive to operate. The objective of this portion of the project is to develop a sensing system that can determine the plant water status quickly. Based on the energy balance model for a single leaf, the temperature difference between the leaf and the surrounding air can be shown to depend on leaf conductance, net radiation, vapor pressure deficit, and wind speed. Leaf conductance is a major plant parameter limiting evapotranspiration rate that influences leaf temperature. Leaf conductance depends upon many factors. During the midday period, the time that plants experience maximum water stress, stem water potential is the major factor that controls leaf conductance. The other factors that influence leaf temperature are vapor pressure deficit, solar radiation, and wind speed. A sensor suite, consisting of an infrared thermometer, quantum sensor, pyranometer, ultrasonic anemometer, and air temperature and relative humidity probe, has been developed to measure leaf temperature and microclimatic information in the vicinity of the leaf to determine plant water stress. Experiments were conducted to test the validity of this sensor suite.

OBJECTIVES AND PROCEDURES

<u>Objective 1</u>- Continue refining light interception/yield relationship for walnut. This included using the mobile platform in ongoing pruning, clonal rootstock and variety trials as well as grower orchards (Table 1). Then, the same row middles were picked up with the new loadcell and GPS equipped supercart. In addition, several sets of diurnal measurements (every two hours from sunrise to sunset) were done each year.

<u>Objective 2</u>- Work continued on development of methods of stress sensing. In 2013 and 2014, a leaf monitor for measuring shaded leaf temperature on a continuous basis was refined and tested in the field. UC Davis has applied for a patent for this device. Continuous leaf monitors were installed on shaded walnut leaves (Fig. 13) at Nickel's Soil Lab, Arbuckle, CA. Leaf monitors were integrated into an existing eKo wireless sensor network at the field site used for precision irrigation control. Leaf monitor data was collected every 15 minutes from July through early October. These data were stored in a database on the field computer at the base station and were available to access in real-time from the web. Plant water status was also measured to ground-truth data. Midday stem water potential for each tree on which a leaf monitor was installed was measured using the pressure chamber after enclosing a shaded leaf in a mylar bag for at least 20-30 minutes.

<u>Objective 3</u>- Finish developing and calibrating an iPhone application designed to let growers estimate canopy light interception and yield potential in their orchards.

RESULTS AND DISCUSSION

Objective 1- Midday canopy light interception varied from about 5 to 95 percent in the orchards studied in 2009-2014 (Fig. 1). Orchards that produced higher than expected yields one year (for their level of light interception) generally produced less in the following year. Yield data was lost at several sites in most years due to problems with scheduling harvests with growers and/or due to early fall rains making plot harvest difficult to fit within the grower harvest schedule.

One Tulare on Paradox orchard in the study, planted at 24 x 25' foot spacing, has produced yields that have averaged right on the optimal line for the past five years (orchard age 9-13 years). Data from this trial are shown in Table 2. Yields have averaged 4.2 tons per acre for the past 5 years and the yield per unit photosynthetically active radiation (PAR) intercepted has averaged 0.049 tons per 1% PAR intercepted which is essentially right on the 0.050 value we would expect if the orchard is on the optimal line. This orchard has a central leader tree structure with 80-90% light interception and the grower does some minimal pruning to maintain tree shape but so far this has not had a negative impact on PAR interception or yield.

These data can be used to assess orchard performance in a number of ways with some examples shown in Figure 2. Fig. 2a shows data from a Chandler rootstock trial in San Joaquin County comparing seedling Paradox rooted trees to trees rooted on clonal rootstocks. Although the canopy PAR interception is about at the level we would expect for this age of orchard (about 10% increase per year is typical for well managed orchards), the yield per unit light intercepted was quite low in years 4-6 suggesting there may be some management improvements that could be improve orchard performance. Fig. 2b shows data from another trial comparing Tulare on seedling Paradox to Tulare on clonal rooted trees. Again, although the canopy is reasonable for the age of the orchard, the productivity is low as seen by the distance below the optimal line. Fig. 2c shows data from a pruning trial on Chandler walnuts at Nickels Soil Lab near Arbuckle in Colusa County. Fig. 2d shows data from a Tulare on Paradox orchard that is the highest yielding orchard in our light bar trial for walnut. This orchard has averaged just above 4 tons per acre (see Table 2 for details). You can see that it is alternating around the optimal line.

These methods allow us to assess how fast an orchard is growing relative to other orchards (how fast they move from right to left on the graph) and also how productive they are per unit PAR intercepted (how close they are to the optimal line). This should be of great benefit to growers since they can then try to determine what factors are causing the slow canopy growth and/or the low production per unit PAR intercepted.

Measurements were also done throughout the season in a Howard pruning and hedging trial as well as a younger Chandler pruning trial at Nickels Soil Laboratory in Colusa County in 2010-2014. Midday canopy light interception was fairly constant through the season for the more mature Howard pruning trial shown in Fig. 3. This suggests that measurements on mature orchards can probably be done from early June to late August with similar results. Seasonal midday canopy light interception through the 2012 season for the Chandler pruning trial is shown in Fig. 4. There were no significant treatment differences at any point during the season. However, the large seasonal change in midday canopy light interception in the younger Chandler orchard (Fig. 4) compared to the older Howard orchard (Fig. 3) suggests that the seasonal timing of measurements in young orchards is much more critical. For instance, the minimal pruned treatment increased from about 46 to 56 percent midday canopy PAR interception from late May to late September in 2012 (Fig. 4). This is a significantly slower rate of increase in canopy cover compared to the previous year. By 2013, there was little change in PAR interception in this orchard from May through September (Fig. 5).

There are instances where the PAR and yield per unit PAR intercepted data can tell different stories. Fig. 6a shows the PAR data for a clonal rootstock trial being conducted by Joe Grant in San Joaquin County. In general, PAR increases for all of the clones in a regular fashion. However, Fig. 5b shows the data for the yield per unit PAR intercepted and in this case, the own-rooted Chandler trees show quite a different story. It appears that they remain vegetative for a longer period of time compared to all of the other rootstocks but by 2013, they were producing in line with everything else. However, in 2014 the yields for the own-rooted trees were again lower Fig. 6).

Midday canopy PAR interception increased with orchard age until about 10-12 years when it tended to flatten and approach a value of near 93 percent (Fig. 7). The potential rate of increase in years 1 to 10 is about 10% per year. The rate is dependent on tree spacing, variety, rootstock, water management, etc. These data are useful in evaluating the performance of a given orchard in relation to others of a similar age, planting configuration, etc.

The relationship between PAR interception and reflected light index (Fig. 8a) and the Diamond relative value (Fig. 8b) suggests that as PAR interception increased, these is a tendency towards darker nuts (lower RLI) and decreased relative value. The results for percent shriveled (Fig. 9a) and moldy nuts (Fig. 9b) show similar trends. In particular, the percentage of moldy nuts appeared to increase with increasing PAR interception (Fig. 9b). The relationship between midday canopy PAR interception and percent edible yield was less clear although the percent edible yield tended to become more variable at high levels of PAR interception (Fig. 10).

Orchard floor temperature- The impact of midday canopy light interception on soil surface temperature is shown in Figure 11. There is a clear relationship between midday canopy light interception on the left side of the light bar and soil surface temperature with the high soil temperatures (approximately 60°C) occurring when midday canopy light interception is low. Even though this orchard is only three years of age, the cool temperatures that are associated with shaded orchards are beginning to show up underneath the tree canopy as shown by the 30°C temperature reached under the tree on the right as it reaches about 90% light interception (Fig. 11). Figure 12 shows similar data for a mature Tulare planting that has produced 4 tons per acre for the past three years (same orchard described in Table 2). Note that the high temperatures coincide with the lowest PAR interception and the low temperatures with the highest PAR interception. These data will be useful in assessing impacts of different canopy management regimes on soil surface temperature which can relate to food safety risk since ideal temperature for *Salmonella* survival in the soil is in the range of 30-35 deg. C which is in the range the shaded areas in walnut orchards generally reach in the Central Valley of California during mid-summer. Because mature walnut orchards tend to be heavily shaded, and this results in near optimal temperatures for *Salmonella* growth and survival, the potential for food safety risk cannot be ignored.

Objective 2- Continuous measurements of leaf temperature and other relevant microclimatic parameters would be helpful to develop plant indices like the crop water stress index (CWSI). A sensing system called the “leaf monitor” (Figure 13) was developed to continuously measure leaf temperature and microclimatic variables and to transmit measured data over the web. A large number of these leaf monitors have been installed in an walnut orchard at Nickels Soil Lab near Arbuckle to continuously monitor leaf temperature, air temperature, relative humidity, wind speed and PAR to predict plant water status. Data collected from preliminary field experiments was used to calculate a daily crop water stress index (CWSI) value which is independent of light and wind conditions. UC Davis has filed for a patent on the leaf monitor.

A modified crop water stress index (MCWSI) was developed to deal with temporal variation in results. Data were analyzed in with the SAS software package (SAS Institute, Inc. v.9.3 Cary, NC). Data from 10:00AM to 4:00PM were selected and a moving average for four data points (one hour data) was used for smoothening. An index was calculated by developing fully water-stressed baselines. Trees were irrigated at night and first or second day after irrigation were considered as fully watered conditions, as it was seen from pressure chamber data that some trees were taking two days to totally recover from water stress after irrigation. The purpose of the leaf monitor is to capture the temporal variation in leaf temperature in relation to plant water stress and environmental conditions and use this information to aid in irrigation scheduling. Results from a time series after an irrigation event is shown in Fig. 14. Fully-watered baselines corresponding to each irrigation event resulted in very high coefficient of determination values, in range of 0.95 to 0.99 for all trees for first day after irrigation. MCWSI values were calculated for 1 to 4 PM using these baselines for walnut. Daily average MCWSI value was calculated for each tree using these instantaneous values. Figure 15 shows a typical pattern of MCWSI curve over consecutive days for an irrigation event of a walnut tree. The value of the MCWSI tended to decrease for 2 days following irrigation (Fig. 14). From the third day onwards CWSI increased rapidly at first, and then after a few days MCWSI curve plateaued. This curve shows that transpiration from the leaf surface was decreasing for the first few days reaching a very low level with increasing water stress. These data suggest the leaf monitor may be useful for irrigation scheduling.

Objective 3- Extensive work was done refining and calibrating the iPhone app for estimating midday canopy light interception in orchards. A flow chart showing the process of using the app is shown in Fig. 15.

The photos need to be taken within one hour of solar noon at an angle such that 4 or more tree trunks are in view, and a complete clear sky day. Branches hanging down or tall weeds in front of the orchard floor shadow image can cause problems. You should take at least five pictures that cover the range of variation in canopy cover in the orchard. If there is a lot of variability, more photos are required to get a good estimate.

The application is calibrated to estimate the PAR interception walnut. A photo (or series of photos) are taken of the shadows on the orchard floor within one half hour of the time the sun is directly overhead. To process the images the user manually positions a polygon on the section delimited by 4, 6 or 9 tree trunks, and then enters the number of trees spaces that this polygon has covered. The image is then processed by first flattening the perspective of the image and then estimating how many pixels in the image are in the shade. You can decide if a particular image has been successfully processed. If not, the image can be reprocessed or discarded.

The application sends results in a pdf as well as comma separated file formats to a provided e-mail address (Fig. 16). In the pdf file you can check all the pictures and the processed images with the estimated PAR. A map is also created showing the location of the images. The .csv file has all the information from the orchard, location name, tree spacing and row spacing, the estimated PAR value, coordinates of the pictures and the number of trees covered by each image. Every record will also show the threshold value where brightness values do not correspond to a shaded pixel.

Plans for 2015- The first objective will be to further refine the relationship between midday canopy light interception and yield as well as the impact that alternate bearing has on the relationship. With a better estimate of the maximum productivity per unit light interception, these data can be used to assess potential orchard yield and will allow separating out canopy light interception as a variable in other research projects. Much of this work is done in conjunction with other ongoing almond research projects to leverage the data. 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 in initiated. The second objective of this project in 2015 will be to complete calibration and release of a new iPhone application that we have developed that can be used to estimate canopy cover from taking a photo of the tree shadows. The plan is to release the iPhone app to farm advisors and select growers in the spring of 2014 for evaluation.

ACKNOWLEDGEMENTS

Thanks to the California Walnut Board and Diamond Foods, Inc. for funding this work.

Table 1. Description of sites used for walnut light interception and yield mapping in the 2014 season. A total of 16 sites were mapped in 2014 but many were mapped multiple times during the season making the total number of light bar runs at 31.

County	Site	Variety	Date mapped	County	Site	Variety	Date mapped
Colusa	Nickels Chandler Pruning trial Arbuckle	Chandler	4/27/14, 4/30/14, 5/21/14, 8/20/14 and 9/17/14	Lake	Walnut pruned versus unpruned trial Kelseyville	Chandler	10/4/2014
Colusa	Nickels Howard Hedging trial Arbuckle	Howard	4/17/13, 5/22/13 and 8/20/14	Merced	Merced Walnut Pruning trial Winton	Chandler	9/16/2014
Colusa	Nickels 1000 Canker trial Arbuckle	Chandler	6/30/14, 8/20/14 and 9/17/14	San Joaquin	CONCAR Walnut Rootstock trial Linden	Chandler	9/12/2014
Colusa	Nickels Chandler Irrigation Monitoring trial Arbuckle	Chandler	4/27/14, 5/21/14, 7/18/14, 7/24/14, 8/20/14 and 9/17/14	Solano	Clonal Walnut Rootstock trial Dixon	Chandler	9/8/2014
Contra Costa	WIP Walnut Rootstock trial Brentwood	Chandler	10/11/2014	Tehama	Walnut lightbar site Red Bluff	Chandler	9/10/2014
Kings	Kings County Walnut MBA trial Hanford	Tulare	9/15/2014	Tehama	CAPEX Mature Walnut EC trial	Chandler	9/9/2014
Lake	Walnut lightbar site Upper Lake #1	Chandler	10/3/2014	Tehama	CAPEX Walnut various ages Corning	Chandler	10/1/14 and 10/2/14
Lake	Walnut lightbar site Upper Lake #2	Chandler	10/3/2013	Tehama	Tehema Walnut Irrigation trial	Chandler	6/11/14 and 9/11/14

Table 2. Midday PAR interception, yield and yield per unit PAR intercepted for the highest yielding orchard in our walnut light bar study. This orchard has produced right on the theoretical line for the past 5 years.

Year	Orchard age (years)	Midday PAR interception (%)	Yield (tons/ac)	Yield per unit PAR intercepted
2009	9	81.8 b	4.60 a	0.056 a
2010	10	84.5 ab	3.91 b	0.046 b
2011	11	88.9 a	4.38 a	0.051 ab
2012	12	89.8 a	4.47 a	0.050 a
2013	13	89.7 a	3.79 b	0.042 c
average		**86.9**	**4.23**	**0.049**

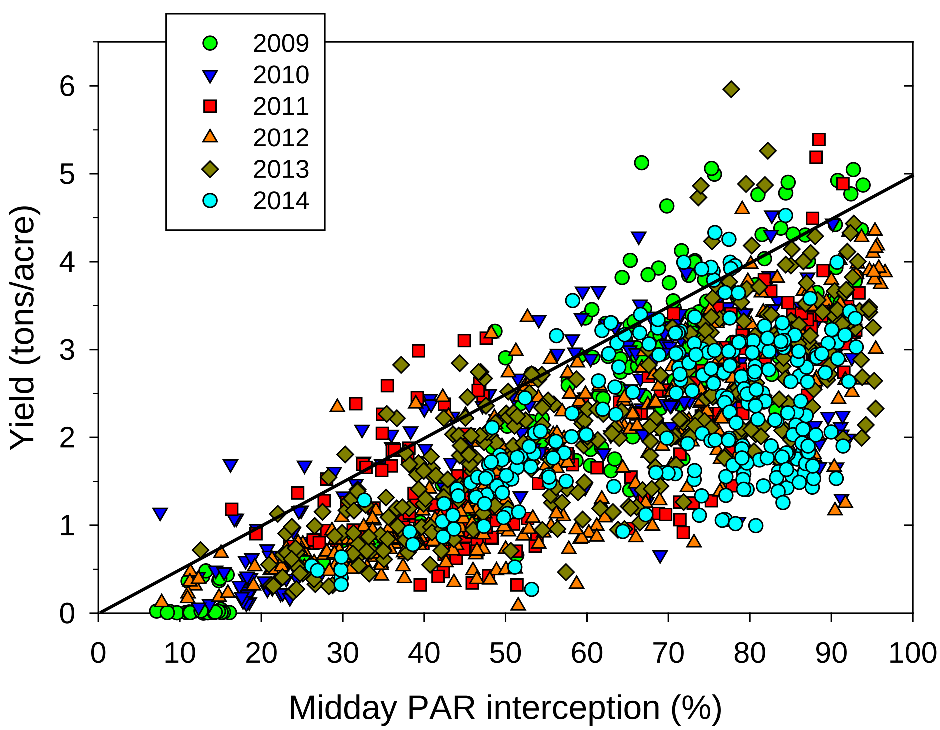

Fig.1. Midday canopy light interception versus yield relationship from various walnut trials from throughout state measured with the Mule mounted light bar in 2009-2014. The solid black line is the estimated upper limit about which the best orchards can alternate.

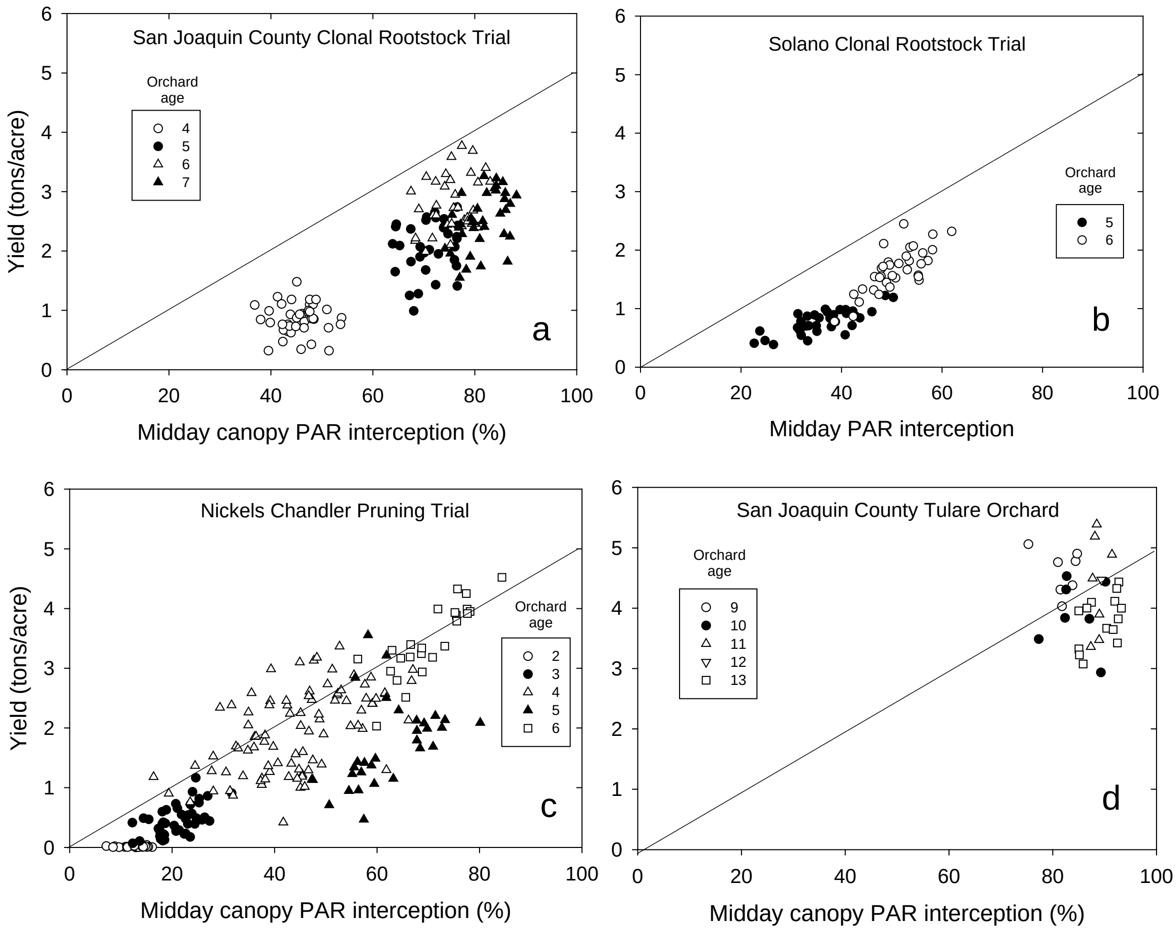

Fig.2. Midday canopy photosynthetically active radiation interception (PAR) verrsus yield for a rootstock trial in San Joaquin County (a), a rootstock trial in Solano County (b), a pruning trial at Nickels Soil lab in Colusa County (c) and a mature Tulare orchard in San Joaquin County (d).

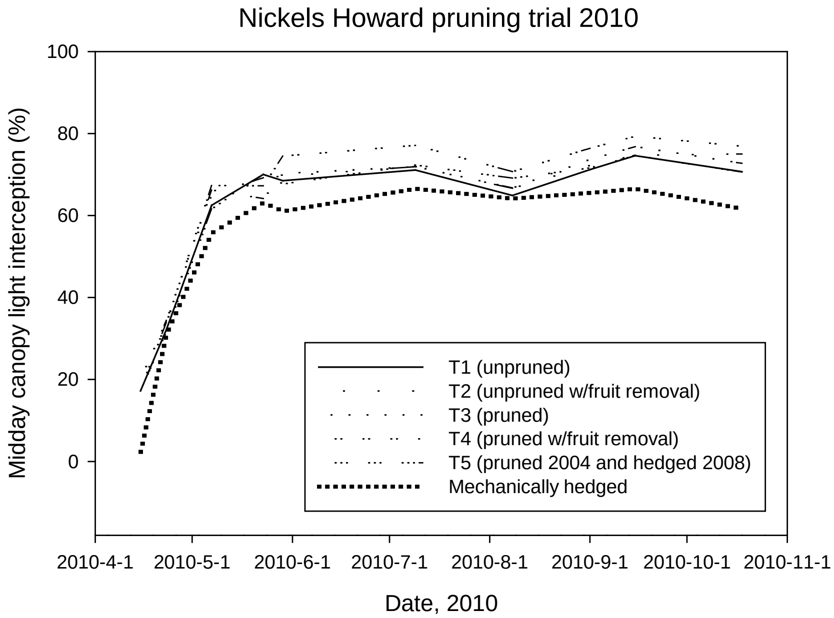

Fig. 3. Midday canopy light interception for the Nickels Howard pruning trial over the 2010 season by pruning treatment.

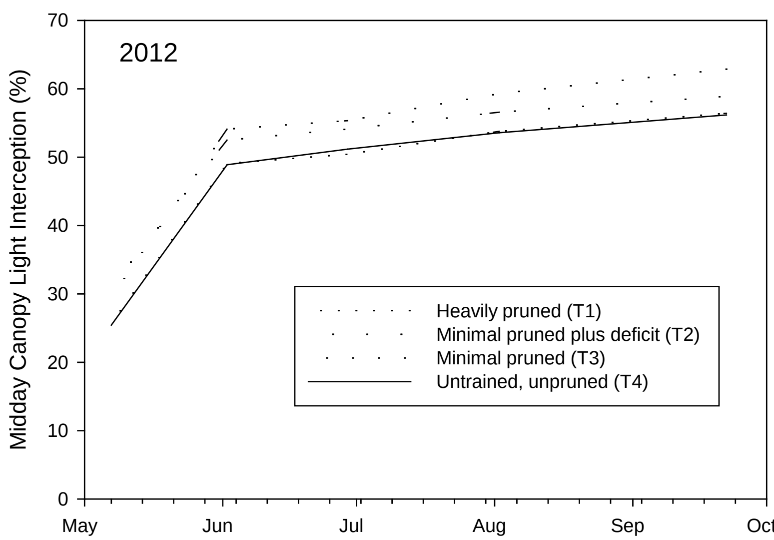

Fig. 4. Midday canopy light interception over the 2012 season for the Nickels Chandler pruning trial. There were no significant treatment differences on any date in 2012.

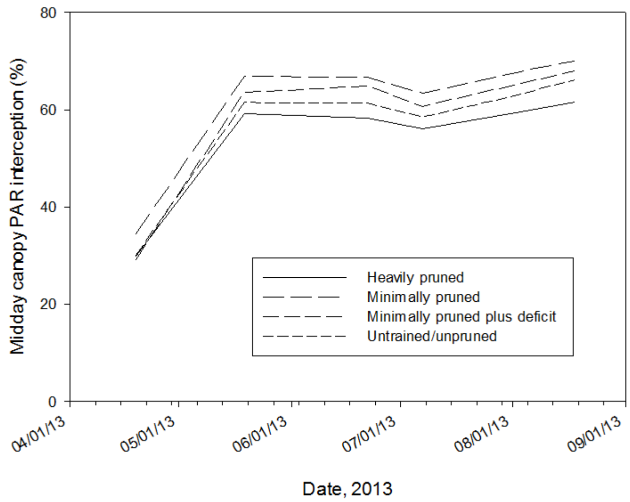

Fig. 5. Midday canopy light interception over the 2013 season for the Nickels Chandler pruning trial. There were no significant treatment differences on any date in 2012. Arrow indicates point where lower canopy branches were removed from all treatments to allow herbicide applications and view of trunk for shaking.

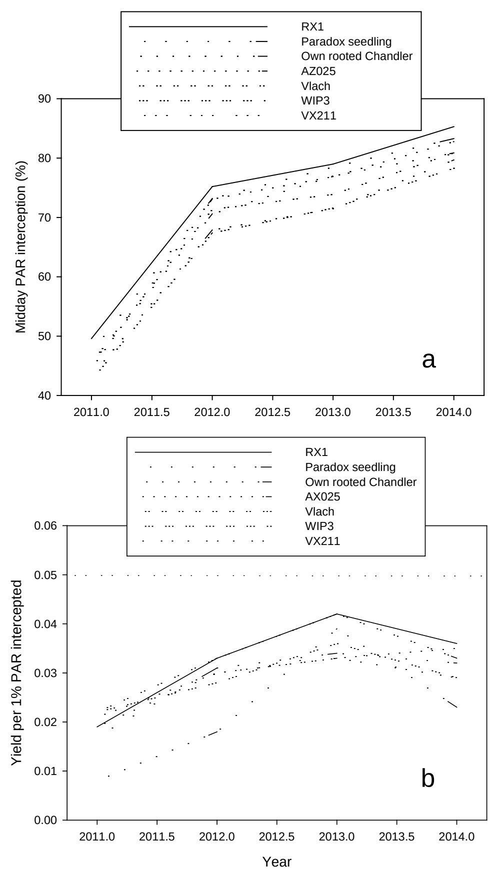

Fig. 6. Midday PAR interception (a) and yield per 1% PAR intercepted (b) over the 2011 to 2014 seasons for a clonal rootstock study in San Joaquin County. Note different pattern for own rooted Chandler compared to other rootstocks.

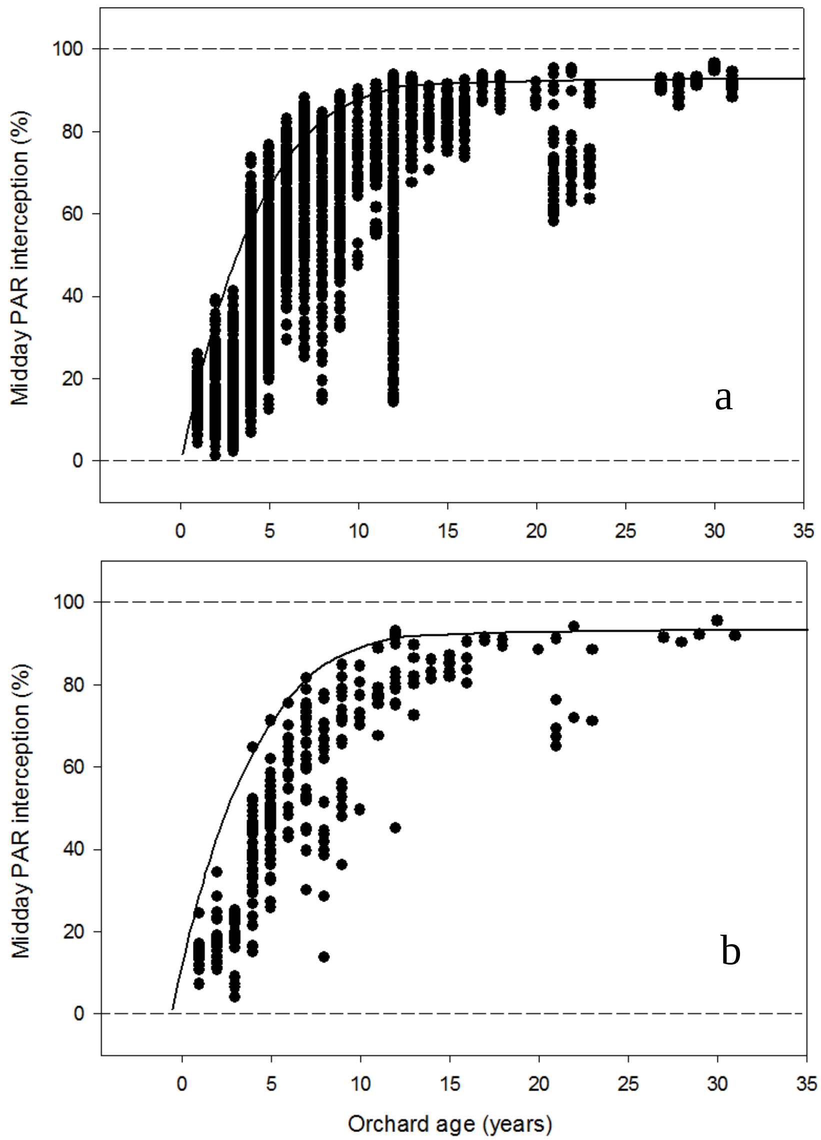

Fig. 7. Midday canopy light interception versus orchard age for all walnut sites from 2009 to 2014. Data is shown for each individual measurements (a) and for the same data but averaged by each site and year (b).

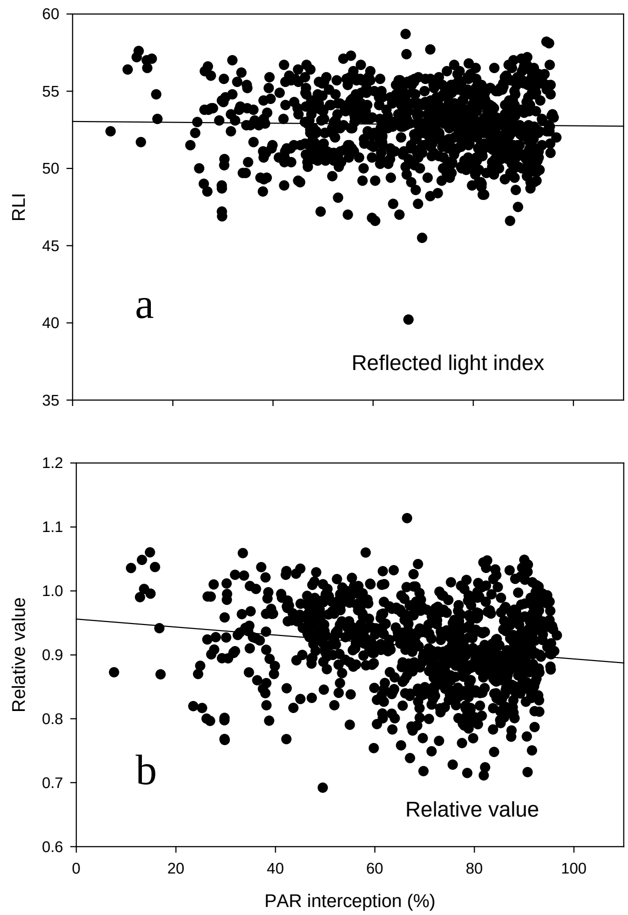

Fig. 8. Reflected light index (a) and relative value from Diamond quality assessment (b) versus midday canopy PAR interception for all data from 2009-2014.

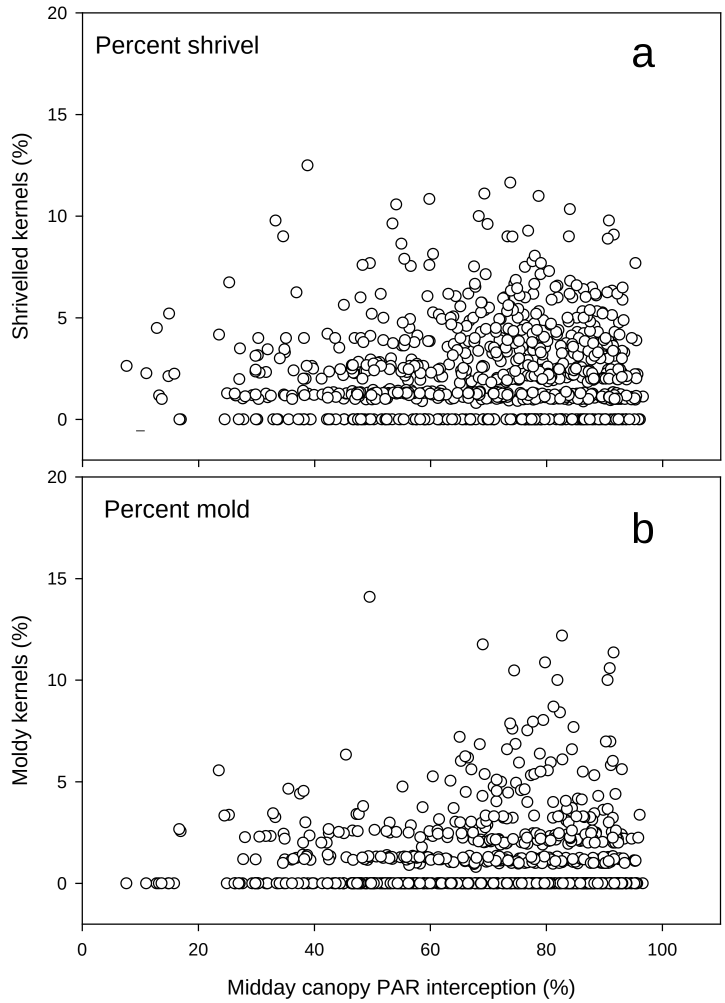

Fig. 9. Percent shriveled (a) and percent moldy nuts (b) versus midday canopy PAR interception for all data from 2009-2014.

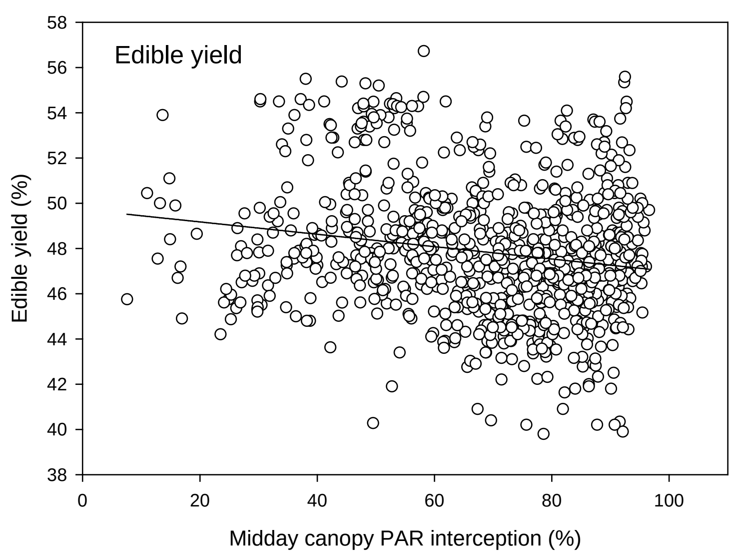

Fig. 10. Percent edible yield versus PAR interception for all data from 2009-2014.

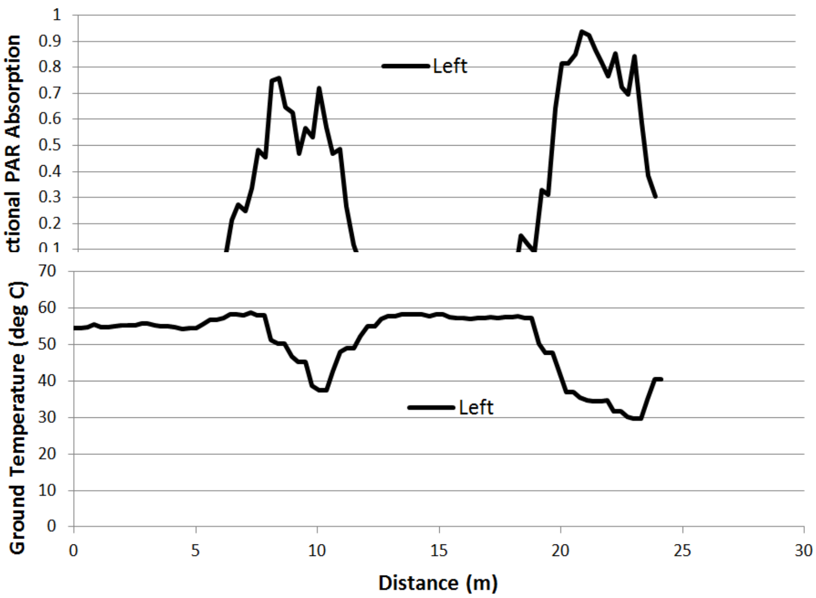

Fig. 11. The top graph shows fractional midday PAR interception (multiply by 100 to get percent midday PAR interception) while the bottom graph shows orchard floor temperature (in degrees Centigrade) for the corresponding drive row center for a methyl bromide alternatives trial in Kings County, California measured on Aug. 30, 2011.

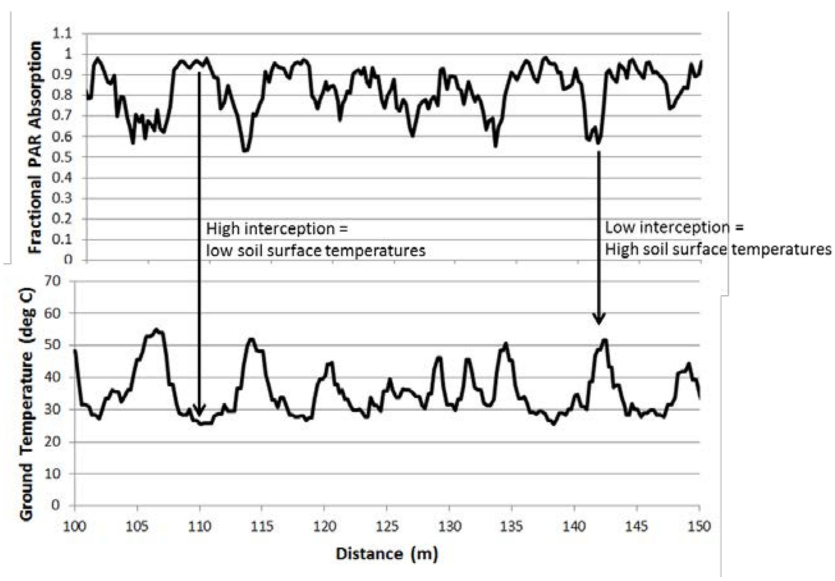

Fig. 12. The top graph shows fractional midday PAR interception (multiply by 100 to get percent midday PAR interception) while the bottom graph shows orchard floor temperature (in degrees Centigrade) for the corresponding drive row center for a mature Tulare walnut orchard in San Joaquin County that has produced an average of 4 tons per acre for the past three years. Data collected on 7/30/2011.

Figure 13: Leaf monitor installed in the lower, shaded canopy of a walnut tree.

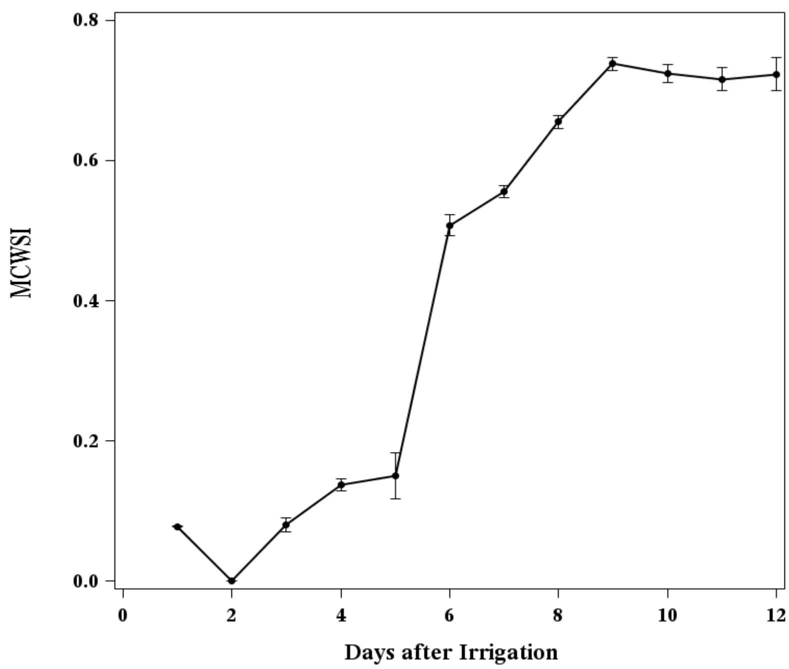

Fig. 14. Pattern of modified crop water stress index (MCWSI) following an irrigation event in Chandler walnut.

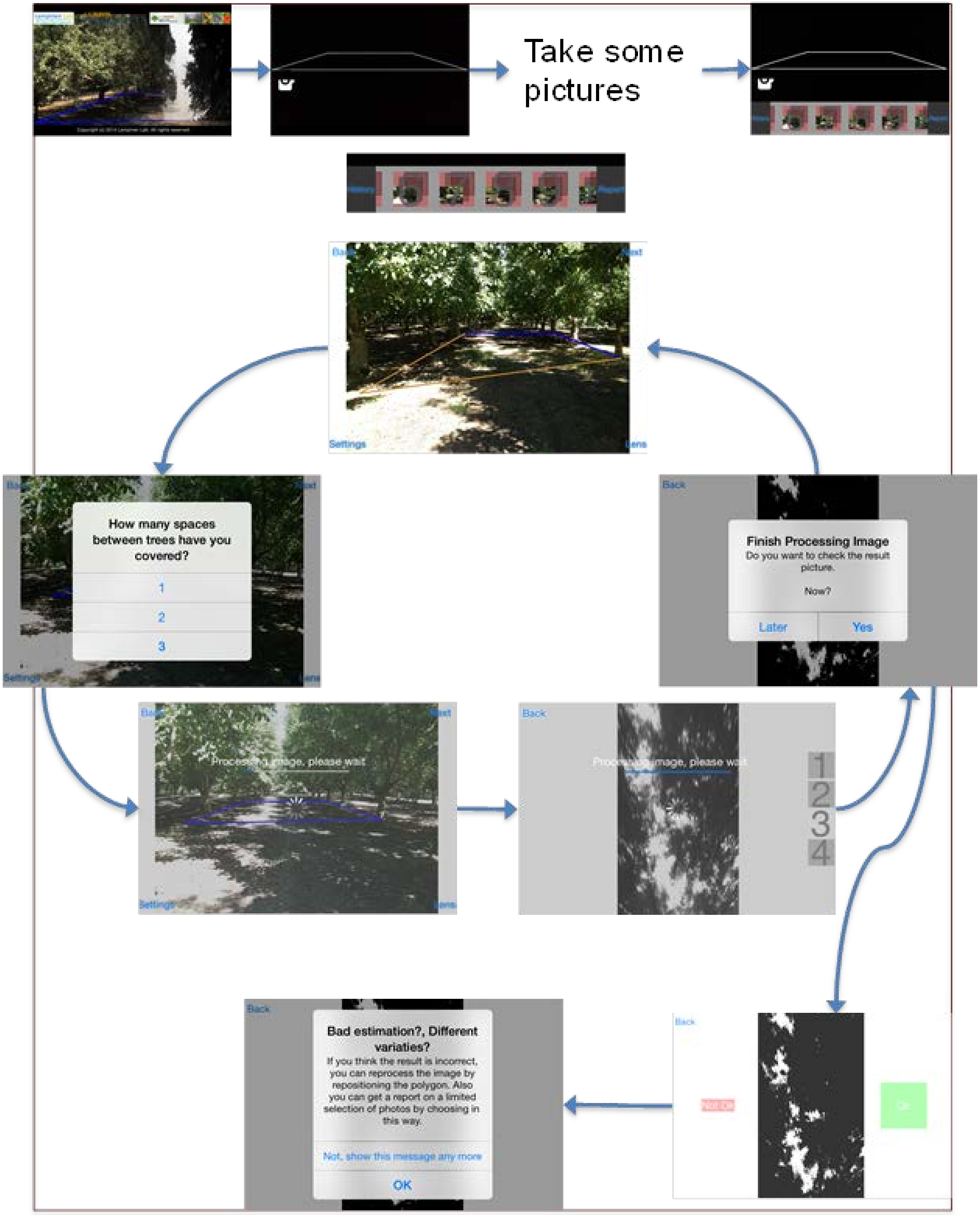

Fig. 15. Flow diagram for iPhone app for estimating midday canopy photosynthetically active radiation interception from photos of the shadows on the orchard floor.

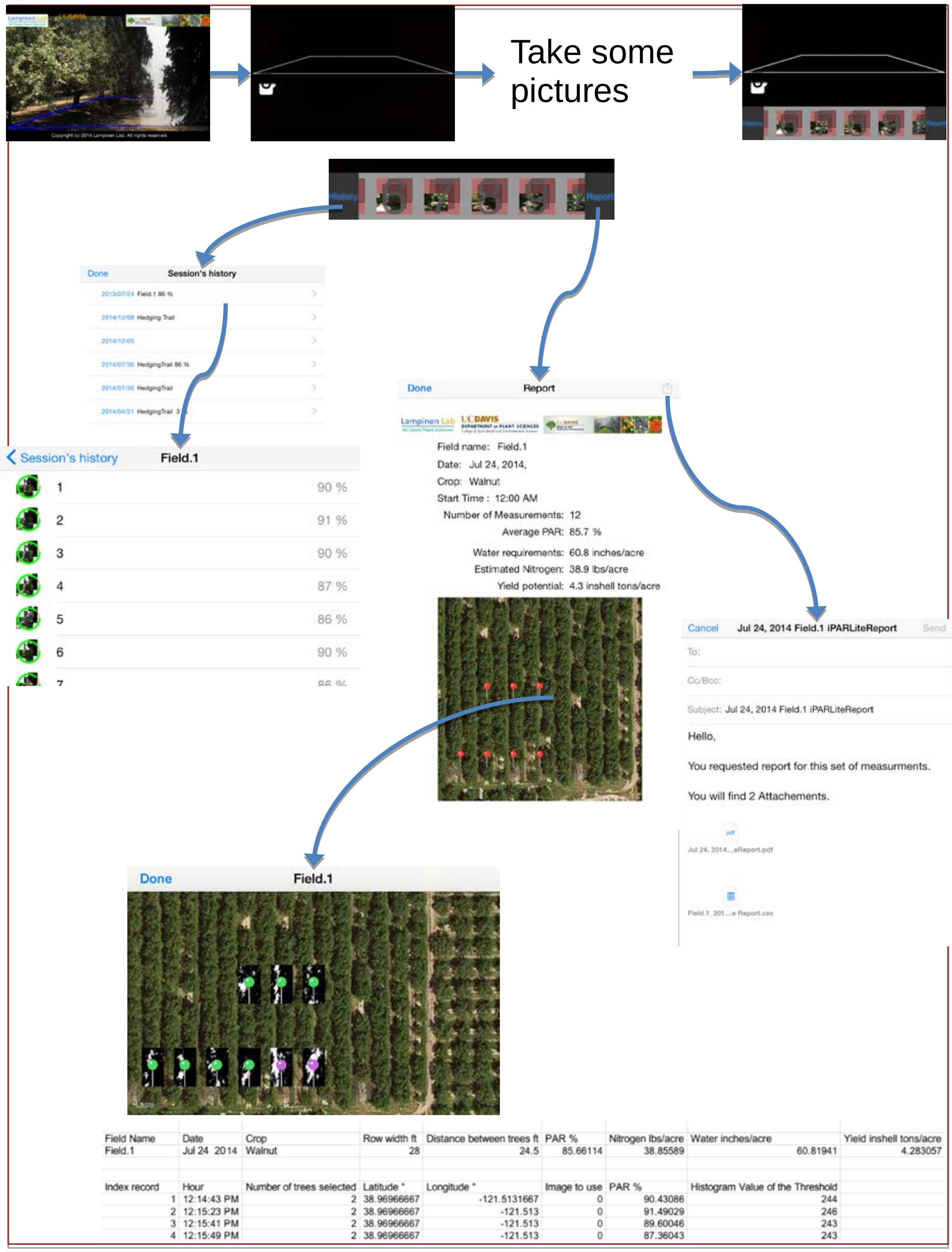

Fig. 16. Diagram showing how reports are generated from the iPhone app. The reports includes a summary of the light interception values as well as the GPS coordinates for each photo taken and also plots the points where photos were taken on a Google Earth map. A detailed report showing each image and value and/or a summary report in an Excel table can be sent by email to the user.