Technology and Product Reports

A Mobile Platform for Measuring Canopy Photosynthetically Active Radiation Interception in Orchard Systems

Bruce D. Lampinen[1,4], Vasu Udompetaikul[2], Gregory T. Browne[3], Samuel G. Metcalf[1], William L. Stewart[1], Loreto Contador[1], Claudia Negrón[1], and Shrini K. Upadhyaya[2]

Additional index words. almond, walnut, *PAR* interception/yield relationships, light interception, yield

Summary. **A mobile platform was developed for measuring midday canopy photosynthetically active radiation (*PAR*) interception in orchards. The results presented are for almond (*Prunus dulcis*) and walnut (*Juglans regia*), but the mobile platform can be used in other orchard crops as well. The mobile platform is adjustable to accommodate orchard row spacing from 4.8 to 7.8 m and is equipped with a global positioning satellite (GPS) receiver and radar for positional assessment as well as three IR thermometers for measuring soil surface temperature. Data from the mobile platform are logged at 10 Hz and stored on a data logger. Custom software has been developed to process the data. The mobile platform was used extensively for mapping midday canopy *PAR* interception in almond and walnut orchards in 2009 and 2010. The mobile platform produced comparable results to those collected with a handheld light bar with the advantage of being able to cover much larger areas and compare these data to mechanically harvested yield data over the same area. For almond orchards, midday canopy *PAR* interception peaked at ≈70% at an orchard age of ≈12 years. For walnut orchards, midday canopy *PAR* interception continued to increase to ≈15 years of age and peaked at a level above 80%. The mobile platform was also able to follow seasonal development of midday canopy *PAR* interception in young and mature orchards. This technology has potential for evaluating new varieties in terms of productivity per unit *PAR* intercepted, in evaluating hand pruning or mechanical hedging practices in terms of impact on *PAR* interception/productivity as well as evaluating effectiveness of insect or disease management treatments. It also has potential as a reference point for grower self-assessment to evaluate orchard canopy development compared with other orchards of similar variety, spacing, etc. Finally, this technology could be used as ground truth referencing for remotely sensed data.**

A relationship between increasing midday canopy *PAR* intercepted by orchard tree canopies and increasing productivity has been well documented (Jackson, 1980; McFadyen et al., 2004, Robinson and Lakso, 1991; Wagenmakers and Callesen, 1995). However, collecting data on canopy light interception in orchards is time-consuming, and it is difficult to measure large areas. Several different methods of estimating canopy light interception have been used including fisheye photography (Robinson and Lakso, 1991). Wunsche et al. (1995) used a series of light sensors moved on a trailer through the orchard, while Giuliani et al. (2000) used a portable light bar with 48 phototransistors and a Teflon diffuser. A commercially available *PAR*-sensing bar (Ceptometer; Decagon Devices, Pullman, WA) was used by Grossman and DeJong (1998) and McFadyen et al. (2004) to take multiple readings in a regular pattern under the trees. Although all of these methods can provide useful data, they are all time-consuming, which makes it difficult to measure light interception in large areas of the orchard.

The authors have used the methods described by Grossman and DeJong (1998) to collect *PAR* interception data using a hand light bar (unpublished). However, the area covered by the hand light bar is small. Since both almonds and walnuts are mechanically harvested, it is difficult to cover large enough areas with the hand light bar to coincide with areas harvested. Therefore, the areas covered with the light bar and harvest data were often not equal.

The mobile platform described here was designed to automate the collection of canopy *PAR* data. This allowed much larger scale mapping of variability in orchard light interception and better comparison with mechanically harvested yield data.

Materials and methods

Mobile platform description. To measure *PAR* intercepted by the plant canopy, a utility vehicle (model 610 Mule; Kawasaki Heavy Industries, Tokyo) was fitted with a *PAR* measurement system (Fig. 1). We will refer to this unit as the mobile platform. The system consists of nine lightweight portable *PAR* sensor bars each 0.8-m long (Decagon Devices). Each sensor bar had two groups of 40 sensing elements with the output from each group of 40 going to separate data logger channels. The light sensing bars were ≈30 cm above the orchard floor during the measurement period. The *PAR* sensing system is in three sections: 1) a 1.6-m-wide section in the middle, 2) two, 1.6-m-wide side sections (one on each side), and 3) two, 1.2-m-wide edge sections (one on each side). The side sections fold back for transportation. The edge sections can be tipped back at an angle toward the back of the mobile platform to change the working width of the system thus making it possible to operate the system in orchards with row spacing from 4.8 to 7.2 m in width. The last 1.2-m width of each of the edge sections is spring loaded and is designed to swing back if it hits a tree trunk or other obstruction to avoid damaging the trees and the instruments. These edge sections are also padded with a rubber bumper to minimize impact damage to the sensor system. The system outputs a total of 18 *PAR* values across the row width. The effective coverage of each of these sensors is 0.4 m across the row except for the sensors located in the edge section (which is variable depending on row spacing). The active width of the edge bars is corrected by taking into account the differing width depending on their angle. Because many almond and walnut orchards are planted at high density, minimally pruned, and have many branches hanging down in the drive row, an aluminum guard was mounted in front of the sensor bars to protect the sensor bars from low hanging tree branches (Fig. 1).

For positional assessment, the mobile light bar was fitted with a GPS receiver (AgGPS 332; Trimble Navigation, Sunnyvale, CA) and a radar unit (P/N 063–0159–835; Raven Industries, Sioux Falls, SD). The GPS unit was used to obtain the location of the utility vehicle when it was outside the orchard when there was a clearer view of satellites and hence more accurate positional data than in the orchards where readings are less accurate due to multipath and dilution of precision errors. The radar was used to obtain the relative position of the utility vehicle with respect to the geo-referenced points when the utility vehicle is within the orchard. Finally, a set of three noncontact IR thermometers (model 6000L; Everest Interscience, Tucson, AZ) was used to measure orchard floor temperature to provide information

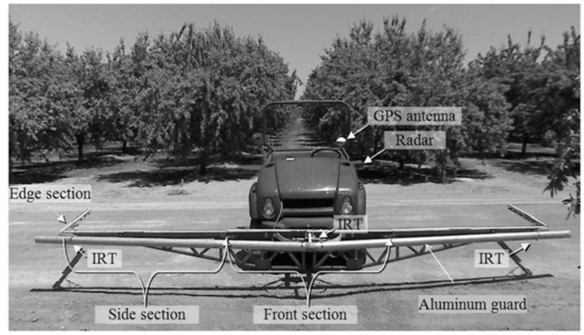

Fig. 1. Mobile platform measurement system retrofitted on a utility vehicle (model 610 Mule; Kawasaki Heavy Industries, Tokyo) for measurement of photosynthetically active radiation (*PAR)* interception in orchards; IRT = IR thermometers, GPS antenna = global positioning satellite receiver antenna.

Table 1. California almond and walnut orchard sites where light bar measurements were conducted in 2009 and 2010. The year indicates when the measurements were conducted and the age indicates orchard age at that time.

County	Variety	Yr (orchard age in years)	Replications (no.)	Replication length (m)[z]
		Almond		
Colusa no. 1	Nonpareil	2009 (11)	11	366
		2010 (12)		
Colusa no. 2	Nonpareil	2009 (12)	64	55
		2010 (13)		
Colusa no. 3	Nonpareil	2009 (3)	40	76
		2010 (4)		
Colusa no. 4	Nonpareil	2009 (13)	60	56
		2010 (14)		
Glenn	Nonpareil	2009 (9)	8	347
		2010 (10)		
Kern no. 1	Nonpareil	2009 (5)	22 (2009)	184
		2010 (6)	48 (2010)	
Kern no. 2	Nonpareil	2009 (14)	12	187
		2010 (15)		
Kern no. 3	Nonpareil	2009 (10)	80	101
		2010 (11)		
Madera no. 1	Nonpareil	2009 (23)	12	401
		2010 (24)		
Madera no. 2	Nonpareil	2009 (6)	24	21
		2010 (7)		
Madera no. 3	Nonpareil	2010 (3)	67	15
Madera no. 4	Nonpareil	2010 (3)	24	9
Madera no. 5	Nonpareil	2009 (3)	36	21
		2010 (4)		
Madera no. 6	Nonpareil	2010 (11)	54	26

(*Continued on next page*)

This work was supported by the Almond Board of California, the California Walnut Board, USDA-ARS Pacific Area-Wide Pest Management Program for Integrated Methyl Bromide Alternatives, and USDA SCRI Grant CA-D-BAE-2082-OD-Precision Canopy and Water Management of Specialty Crops through Sensor-Based Decision Making.

[1]Department of Plant Sciences, University of California, Davis, CA 95616

[2]Department of Biological and Agricultural Engineering, University of California, Davis, CA 95616

[3]USDA-ARS, Department of Plant Pathology, University of California, Davis, CA 95616

[4]Corresponding author. E-mail: bdlampinen@ucdavis.edu.

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.3048	ft	m	3.2808
2.54	inch(es)	cm	0.3937
1.1209	lb/acre	$kg \cdot ha^{-1}$	0.8922
1.6093	mph	$km \cdot h^{-1}$	0.6214
2.2417	ton/acre	$Mg \cdot ha^{-1}$	0.4461
(°F – 32) ÷ 1.8	°F	°C	(1.8 × °C) + 32

Table 1. (*Continued*) California almond and walnut orchard sites where light bar measurements were conducted in 2009 and 2010. The year indicates when the measurements were conducted and the age indicates orchard age at that time.

County	Variety	Yr (orchard age in years)	Replications (no.)	Replication length (m)[z]
Sutter	Nonpareil, Winters, Aldrich	2009 (4) 2010 (5)	12	4
Stanislaus no. 1	Nonpareil	2009 (9) 2010 (10)	54	32
Stanislaus no. 2	Nonpareil	2009 (10) 2010 (11)	48	29
Stanislaus no. 3	Nonpareil	2009 (7) 2010 (8)	38	55
Yolo	Nonpareil	2010 (11)[y]	56	11
		Walnut		
Colusa no. 1	Chandler	2009 (2)[y] 2010 (3)	24	23
Colusa no. 2	Howard	2009 (8) 2010 (9)	56	8
Lake no. 1	Chandler	2009 (7) 2010 (8)[y]	6 (2009) 5 (2010)	373
Lake no. 2	Chandler	2009 (8) 2010 (9)[y]	2 (2009) 7 (2010)	183
Lake no. 3	Chandler	2009 (7) 2010 (8)[y]	6 (2009) 5 (2010)	208
San Joaquin	Tulare	2009 (9) 2010 (10)	7	414
Solano	Tulare	2009 (11)[y] 2010 (12)	6 (2009) 9 (2010)	243
Stanislaus	Chandler	2009 (12)	12	54
Sutter no. 1	Chandler	2009 (27) 2010 (28)	10	275
Sutter no. 2	Chandler	2009 (14) 2009 (15)	10	386
Sutter no. 3	Chandler	2009 (8) 2010 (9)	31	111
Sutter no. 4	Chandler Vina	2009 (7) 2010 (8)	12 (2009) 15 (2010)	23
Yolo	Chandler	2009 (21) 2010 (22)	10 (2009) 20 (2010)	777
Yuba	Tulare	2009 (9)	4	302
Yuba no. 1	Howard	2009 (10)	18	349
Yuba no. 2	Chandler	2009 (3)[y] 2010 (4)	8	9

[z]1 m = 3.2808 ft.
[y]Yield data were not collected.

on potential food safety risk related issues associated with microbial contamination of nuts that are shaken or fall to the ground during harvest. Danyluk et al. (2008) showed that temperatures on the soil surface in a heavily shaded orchard where a *Salmonella* outbreak originated were in a temperature range where *Salmonella* could grow. One of the thermal sensors was mounted at the center of the front section pointing forward and down at the drive row soil surface. The other two thermal sensors were mounted on the left and right edge sections pointing outward to measure orchard floor temperature in the shaded part of the orchard near the tree row (Fig. 1).

Walnut orchards are generally planted with a single variety so the data across the entire light bar were used when calculating percent interception. However, almonds are not self-fertile and therefore orchards are planted with alternating rows of at least two different varieties. Therefore, when measuring in almond orchards, the data from the left and right sides of the light bar was kept separate to allow partitioning of canopy *PAR* interception for each variety independently.

The typical pattern of use for the mobile light bar platform was to take measurements within one-half to 1 hour of solar noon. This minimized errors due to the altitude of the sun. The unit was operated at a speed of ≈10 $km \cdot h^{-1}$ within the orchard to obtain light interception data. This travel speed provided a spatial resolution of ≈0.28 m along the direction of travel at a sampling rate of 10 Hz. All the sensor outputs [18 *PAR* values, radar, and three thermal sensor outputs) were recorded on a data logger (CR3000; Campbell Scientific, North Logan, UT)]. The GPS data were also recorded using the same data logger, but only when the mobile platform light bar was outside the tree rows. The data were analyzed using a custom developed program in Excel (Microsoft, Redmond, WA).

Measurements were started and ended evenly spaced between two trees. Full sun measurements were taken at the beginning and end of each row. In addition, a data logger (Hobo U30; Onset Computer, Pocasset, MA) with a *PAR* sensor (S-LIA-M003, Onset Computer) was set up to log at 1-min intervals outside of the orchard in an unobstructed location nearby. An effort was made to take measurements only under clear skies and the data from this data logger outside of the orchard were used to control for any clouds that passed over during measurements. Only data collected under clear sky conditions were used in the analysis presented.

Previous data collected by the authors had used the same light sensing bar as the mobile platform used but with a Sunfleck Ceptometer data logger (Decagon Devices). The handlight bar was used by walking through the orchard covering a similar area as the mobile platform, but the pattern was quite different (see Grossman and DeJong, 1998, for a description of the pattern used). To compare these two methods, the same walnut orchard was measured with both the handheld and mobile platform light bar in 2009.

Orchard trials. Trials with the mobile light bar were conducted in university research and commercial almond and walnut orchards

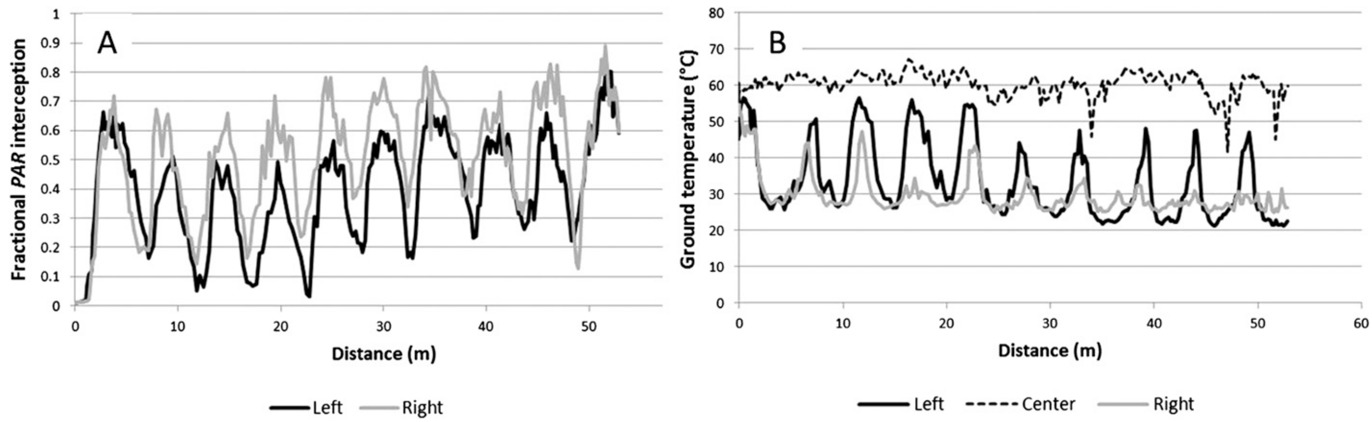

Fig. 2. Typical photosynthetically active radiation (*PAR*) interception (A) and thermal soil surface temperature (B) sensor data for a 3-year-old almond orchard ('Nonpareil' on right side of light bar and pollenizer on the left) on 15 Sept. 2010. (A) *PAR* interception from sensors in the left section and right sections. (B) Ground IR thermometer data for soil surface temperature underneath the 'Nonpareil' tree row canopy (left), middle of drive row (center) and underneath the pollinizer tree row canopy (right); 1 m = 3.2808 ft, (1.8 × °C) + 32 = °F.

throughout California in 2009 and 2010. The goal was to survey orchards of varying ages and planting configurations in both crops. The orchards surveyed in 2009 and 2010 are listed in Table 1. Walnut orchards ranged in age from 2 to 28 years and almond orchards from 3 to 24 years. The most common almond variety (Nonpareil) and the most common walnut variety (Chandler) were the main varieties used in this study, but some other varieties were monitored as well (Table 1).

For almond, the nuts for the varieties where the light bar was run were picked up with the growers' harvester and weighed using a load-cell-equipped harvest trailer or drive-on scales. Subsamples were taken for hulling, drying, and cracking to obtain kernel weight and number of nuts per kilogram of field weight. For walnut, at the time of harvest, the same tree row middles where the light bar was run were picked up with the growers' harvest equipment and weighed using load-cell-equipped trailers or drive on scales. Subsamples were taken for hulling and drying to allow adjusting the rough field weights to dry in-shell weights. The slight difference in techniques for almonds vs. walnuts was used because yield numbers for almond are usually reported as dry-shelled kernel weights, whereas those for walnuts are usually expressed as dry-in-shell weights.

Fig. 3. Geo-referencing information displayed using Google Earth (Google, Mountain View, CA). Flags represent the mobile platform antenna location at point of full sun reading. White lines indicate paths of travel. Image Courtesy of Google and the U.S. Geological Survey (31 May 2007).

Results

The mobile light bar worked well, and typical results obtained using this system are shown in Fig. 2. *PAR* interception for the left and right sections shows the pattern of interception by the individual trees in a 3-year-old almond orchard (Fig. 2A). The soil surface temperatures show the inverse of the light interception data with high temperatures where light interception is low and vice versa (Fig. 2B). The middle of the drive row soil surface temperatures in the 60 °C range is typical for sun-lit orchard floors without groundcover in California during summer. To reference back to the measurement location, the program can also generate keyhole markup language files that can be opened in Google Earth (Google, Mountain View, CA) for visualization of path of the mobile light bar in the orchard (Fig. 3). The flags in Fig. 3 indicate the position of the GPS antenna on the mobile platform at the time the full sun reading, and GPS coordinates were recorded at the beginning of each row.

Figure 4 shows spatial variability in *PAR* interception as measured with the mobile light bar platform compared with the Google Earth image of the same orchard. The *PAR* data

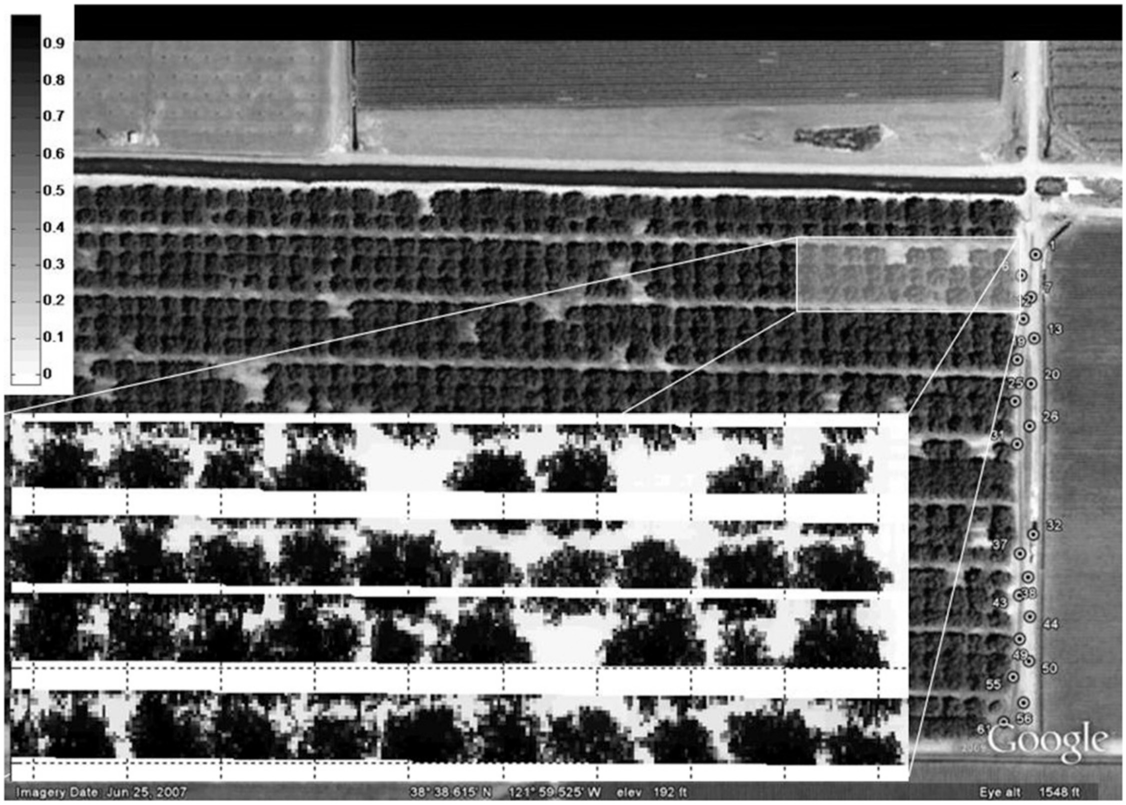

Fig. 4. An overlay of an exploded view of a small part of a walnut orchard in Yolo County, CA, showing the photosynthetically active radiation (*PAR*) absorption at 1300 HR on 10 Aug. 2009. The Google Earth map [courtesy of Google, Mountain View, CA (24 Sept. 2009)] is shown in the background. The grayscale image is a two-dimensional plot of the ratio of absorbed *PAR* to incoming *PAR* above the canopy. The darker regions represent heavy absorption implying higher canopy *PAR* interception. The exploded view was generated using MATLAB (MathWorks©, Natick, MA); 1 ft = 0.3048 m.

shown in this figure is the ratio of sensor data obtained under the tree canopy to the full sun data obtained from outside the orchard boundary. The resemblance between the Google Earth map and the results obtained by our mobile platform *PAR* measurement system is remarkable. However, it should be noted that while the Google Earth map provides the light energy reflected by the plant canopy, our system measures *PAR* actually intercepted by the tree canopy, thus providing a direct measurement of potential energy for photosynthesis that is being captured by the orchard. These data can be used to assess spatial variability in *PAR* interception to evaluate variability for a selected area or the whole orchard.

When all of the *PAR* interception data were plotted against orchard age for the almonds and walnuts, some patterns emerged (Fig. 5). The variability about the line is due to differing management practices, planting densities, varieties, etc., and these issues will be addressed in future publications. For the almond orchards in the survey, the average *PAR* interception peaked at ≈70% at an orchard age of ≈12 years (Fig. 5A). Part of the reason for this might be that at the time of harvest, almonds need to be dried on the orchard floor and this becomes difficult when *PAR* interception gets above 70%. Therefore, when these orchards get overly crowded, they are usually mechanically hedged, hand pruned, or both to allow enough light to hit the orchard floor to dry the nuts at the time of harvest. For walnuts, the *PAR* interception continued to increase to ≈15 years and reached a maximum above 80% (Fig. 5B). The walnut orchards in the 21- to 22-year-old range were pruned with a mechanical hedger. This at least partly explains their relatively low light interception for their age. For both almonds and walnuts, the relative lack of data points at orchard ages above 15 years makes the interpretation of the data above this range less certain.

The mobile platform light bar was also shown to have value in following canopy development over the season. Figure 6 shows the seasonal pattern of midday canopy light interception for a 3-year-old ‘Chandler’ walnut orchard and a 10-year-old ‘Howard’ walnut orchard. The midday canopy light interception for the 10-year-old ‘Howard’ orchard was relatively constant after 1 June, while that for the 3-year-old ‘Chandler’ orchard continued to increase throughout the season (Fig. 6). This suggests that for a mature orchard, the measurement of midday canopy *PAR* interception can be done anytime between early June and October with similar results, while measurements for the younger orchard need to take into account the timing of the measurement during the growing season.

In Summer 2009, a comparison was made between light bar measurements done with a handheld Sunfleck Ceptometer light bar (Decagon Devices) using methods described by

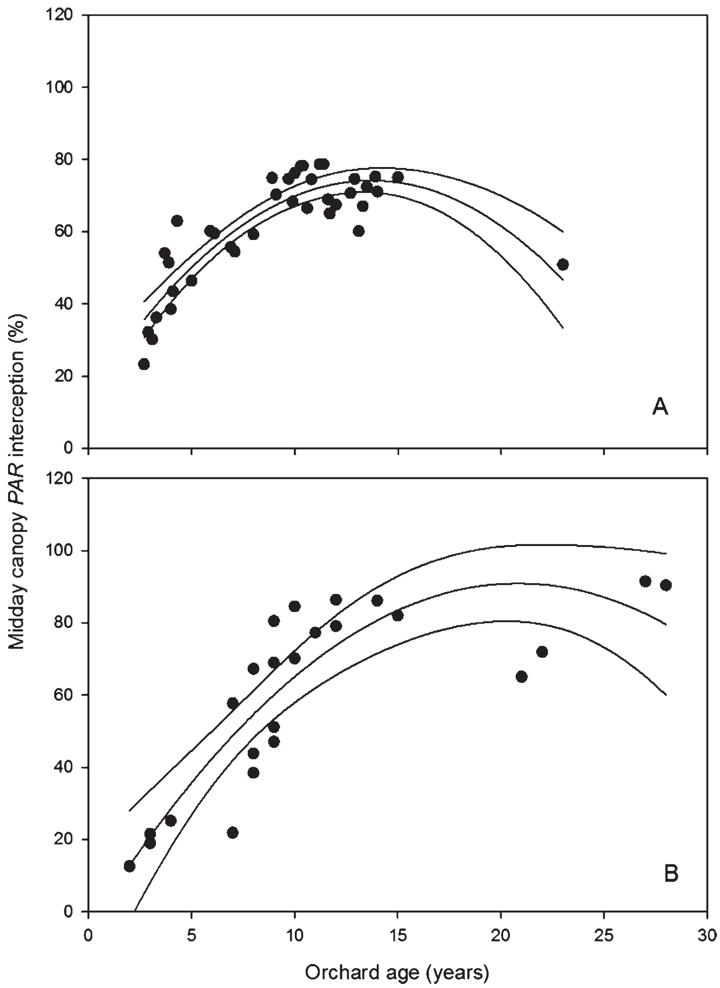

Fig. 5. Orchard midday canopy photosynthetically active radiation (*PAR*) vs. age for all almond (A) and walnut (B) orchard sites. Each point represents the average value for each orchard site. Lines above and below regression line indicate 95% confidence interval calculated using orchard average values (Sigmaplot version 11; Systat Software, San Jose, CA).

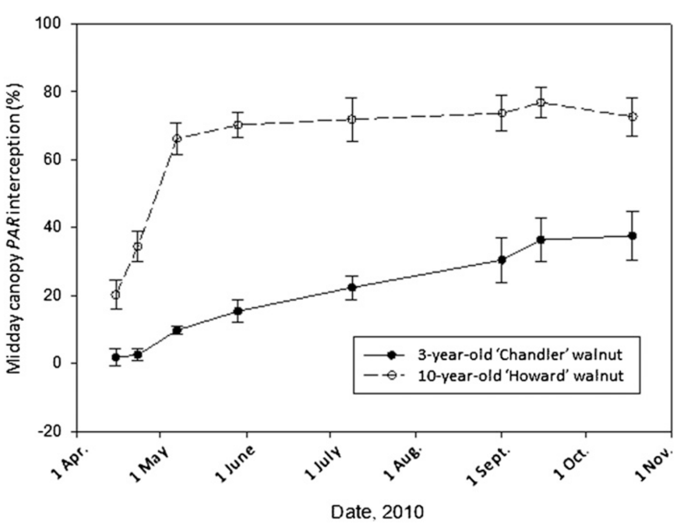

Fig. 6. Midday canopy photosynthetically active radiation (*PAR*) interception for a growing 3-year-old 'Chandler' walnut orchard and a mature 10-year-old 'Howard' walnut orchard in Colusa County, CA, over the 2010 season. Both datasets were for trials with six replications for each data point. Bars indicate ±2 SE calculated using SAS Proc Means (SAS version 9.2; SAS Institute, Cary, NC).

Grossman and DeJong (1998) compared with data from the same area measured with the mobile platform. The resulting correlation is shown in Fig. 7. Although the hand light bar measurements were done ≈1 month before the mobile platform measurements, the graph in Fig. 6 (the 'Howard' orchard in this figure is the same as the one in Fig. 7) suggests that the seasonal change in midday canopy *PAR* interception during this period would have been minimal. The results suggest that the methods produced comparable results since the slope of the line was near one (Fig. 7).

In both almond and walnut, yield generally increased with increasing midday canopy *PAR* interception across the *PAR* range measured from ≈20% to 90% (Fig. 8). To test if the unbalanced design due to unequal numbers of replications at different sites was influencing outcome, regression lines were also calculated for the data using the average data for each site. The regression lines and intercepts changed slightly but were similar for the regression calculated with the whole data set vs. the average data for each site (Fig. 8 legend). The increase in yield that occurred from 20% to 90% *PAR* interception in the current study agrees with data for macadamia (*Macadamia integrifolia*) where yields continued to increase with increasing canopy light interception up to 94% (McFadyen et al., 2004). This contrasts with apple (*Malus ×domestica*) where decreasing yield has been found with increasing canopy light interception above 70% (Verheij and Verwer, 1973). This difference compared with apple may be because for fresh fruit such as apple, the fruit need to be borne in well-lit parts of the canopy. At light interception levels above 70%, there would need to be extensive pruning to keep the bearing areas of the canopy in well-lit positions and the resulting vegetative growth might lead to lower production. Differences in yield for a given level of *PAR* interception in almond and walnut will be investigated in future publications but are likely due to factors such as pruning practices (pruning generates vegetative growth that is less productive per unit *PAR* intercepted for 1–2 years after pruning), variability in weather during bloom, and differences in previous year crop from orchard to orchard.

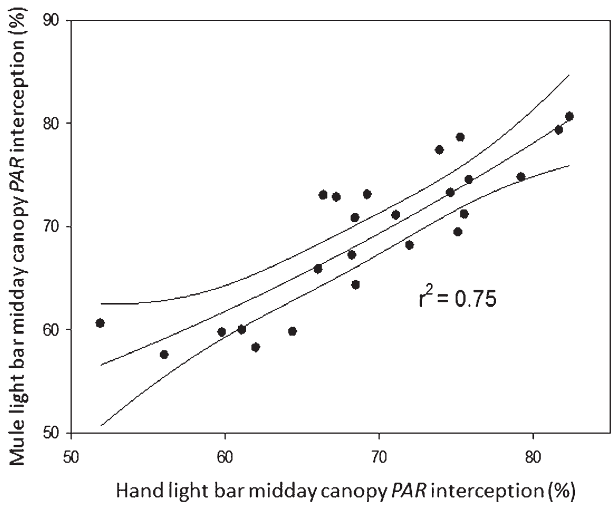

Fig. 7. Midday canopy photosynthetically active radiation (*PAR*) interception for a 9-year-old 'Howard' walnut orchard as measured with a hand light bar (using methods described in Grossman and DeJong, 1998) on 23 June 2009 and the mobile platform light bar on 20 July 2009. Equation for line is $y = 0.948x + 3.823$. Lines above and below regression line indicate 95% confidence interval.

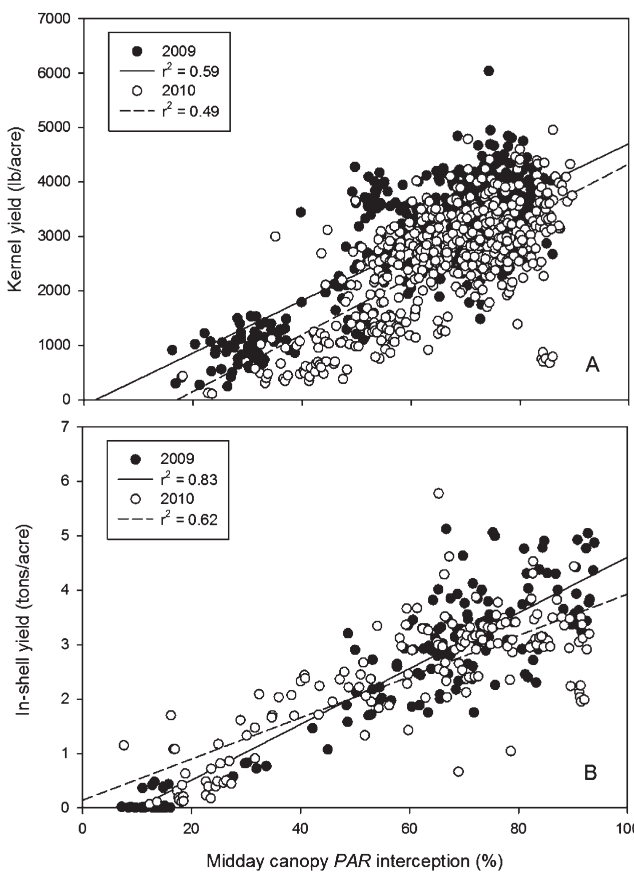

Fig. 8. Midday canopy photosynthetically active radiation (*PAR*) interception vs. yield for all almond (A) and walnut (B) sites in 2009 and 2010. Almond yield data are expressed as kernel pounds per acre and walnut as in-shell tons per acre since this is how the growers are compensated. Equations for lines for all data for almond 2009 ($y = 48.1x + 104.2$), almond 2010 ($y = 52.3x - 893.5$), walnut 2009 ($y = 0.051x - 0.514$), and walnut 2010 ($y = 0.038x + 0.139$). To test if unbalanced design was influencing regression lines, equations were also calculated for mean site data. Equations for lines with mean site data are almond 2009 ($y = 7.5x - 169.9$), almond 2010 ($y = 45.3x - 700.3$), walnut 2009 ($y = 0.050x - 0.611$), and walnut 2010 ($y = 0.034x + 0.279$); 1 lb/acre = 1.1209 kg·ha^{-1}, 1 ton/acre = 2.2417 Mg·ha^{-1}.

Conclusions

The mobile platform was able to measure *PAR* interception in almond and walnut orchards as it varied with orchard age as well as over the course of a season. The mobile platform was adjustable to a range of orchard row widths from 4.8 to 7.8 m and allowed ≈8–18 km of orchard row to be mapped in a 1–2 h window centered about the time when the sun was directly overhead. The software allowed the routes of the mobile platform to be overlaid on Google Earth images. The mobile platform produced comparable results to those collected with a handheld light bar with the advantage of being able to cover much larger areas and compare these data to mechanically harvested yield data over the same area. For almond orchards, midday canopy *PAR* interception peaked at ≈70% at an orchard age of ≈12 years. For walnut orchards, midday canopy *PAR* interception continued to increase to ≈15 years of age and peaked at a level above 80%. The mobile platform was also able to follow seasonal development of midday canopy *PAR* interception in young and mature orchards. In addition, the mobile platform allowed the mapping of soil surface temperatures as it was related to midday canopy *PAR* interception, and this information is useful in assessing food safety risk in almond and walnut orchards where the nut crop is harvested off the orchard floor.

The mobile platform light bar provides a useful tool for assessing the performance of different practices in almond and walnut varieties on a scale that was not feasible in the past. For example, new varieties can be compared with existing varieties to see if they are more productive per unit *PAR* intercepted or if they just grow faster and hence ultimately end up with the same production once the canopy space is filled. Another use is to assess midday *PAR* interception in any orchard relative to other orchards of the same age and variety. If an orchard is intercepting significantly less *PAR* than orchards of similar variety, spacing, and age, then the grower has a tool to track changes that occur with improved management practices. Other uses include evaluating different hand pruning or mechanical hedging regimes in terms of their impacts on canopy *PAR* interception and ultimately productivity. The mobile platform could also be used as a tool to help assess property value based on the relative production potential.

Literature cited

Danyluk, M.D., M. Nozawa-Inoue, K.R. Hristova, K.M. Scow, B. Lampinen, and L.J. Harris. 2008. Survival and growth of *Salmonella* Enteritidis PT 30 in almond orchard soils. J. Appl. Microbiol. 104: 1391–1399.

Giuliani, R., E. Magnanini, C. Fragassa, and F. Nerozzi. 2000. Ground monitoring the light-shadow windows of a tree canopy to yield canopy light interception and morphological traits. Plant Cell Environ. 23:783–796.

Grossman, Y.L. and T.M. DeJong. 1998. Training and pruning system effects on vegetative growth potential, light interception and cropping efficiency in peach trees. J. Amer. Soc. Hort. Sci. 123:1058–1064.

Jackson, J.E. 1980. Light interception and utilization by orchard systems. Hort. Rev. 2:208–267.

McFadyen, L.M., S.G. Morris, M.A. Oldham, D.O. Huett, N.M. Meyers, J. Wood, and C.A. McConchie. 2004. The relationship between orchard crowding, light interception, and productivity in macadamia. Aust. J. Agr. Res. 55:1029–1038.

Robinson, T.L. and A.N. Lakso. 1991. Light interception, yield and fruit quality of 'Empire' and 'Delicious' apple trees grown in four orchard systems. Acta Hort. 243:175–184.

Verheij, E.W.M. and F.L.J.A.W. Verwer. 1973. Light studies in a spacing trial with apple on a dwarfing and semi-dwarfing rootstock. Sci. Hort. 1:25–42.

Wagenmakers, P.S. and O. Callesen. 1995. Light distribution in apple orchard systems in relation to production and fruit quality. J. Hort. Sci. 70:935–948.

Wunsche, J.N., A.N. Lakso, and T.L. Robinson. 1995. Comparison of four methods for estimating total light interception by apple trees of varying forms. HortScience 30:272–276.