MODELING CANOPY LIGHT INTERCEPTION FOR ESTIMATING YIELD IN ALMOND AND WALNUT TREES

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ABSTRACT

A knowledge of spatio-temporal variability in potential yield is essential for site-specific nutrient management in crop production. The objectives of this project were to develop a model for photosynthetically active radiation (PAR) intercepted by almond and walnut trees based on data obtained from respective tree(s) and estimate potential crop yield in individual trees or in blocks of five trees. This project uses proximally sensed PAR interception data measured using a lightbar mounted on a mobile platform and a crop growth model to estimate potential yields of almond and walnut trees. An analytical model was developed to estimate PAR intercepted by the tree in which tree canopy was assumed to be spherical in shape. PAR intercepted by a tree was estimated taking into account the effect of row spacing, tree spacing within the row, latitude and longitude of the orchard, day of the year and row orientation. Scans were collected at solar noon in almond and walnut orchards during the 2012 and 2013 growing seasons. Diurnal scans were also collected during the 2012 season and were used to validate the model. Estimated versus measured data of PAR interception in almond and walnut trees had coefficient of determination of 0.86 and 0.94, respectively. The coefficient of determination for the relationship between actual yield and absolute midday PAR intercepted was 0.81 and 0.63 for almond and walnut trees, respectively. The coefficient of determination for the relationship between actual and potential yield was 0.80 and 0.59 for almond and walnut crops, respectively. Actual yield from those trees with lower values of midday PAR interception was found to be closer to their respective potential yield than those trees with higher values of midday PAR interception. The results suggest that there is a potential to use spatially variable PAR interception data to implement site-specific input management and enhance production.

Key words: PAR interception, lightbar, potential yield, crop growth model, canopy model, tree spacing, almond, walnut.

INTRODUCTION

Accurate information about tree canopy architecture and PAR absorption is useful to estimate potential yield. This information could be very valuable to implement canopy management, and enhance quality and quantity of yield (Lampinen et. al., 2006). Potential yield is a theoretical concept that indicates the yield that a genotype can produce under optimal management in the absence of biotic or abiotic stresses (Acevedo et. al., 2002). In reality, the potential yield can never be achieved, but it can give us an idea of how well the crop was managed and how good the growing conditions were. Moreover, potential yield can assist in making management decisions (e.g. fertilization), especially if this is known early in the season.

The photon flux density within the PAR range (400 – 700 nm) is used by plants in photosynthesis (Jones, 1992). Since there is a direct relationship between quantity of PAR absorbed and the amount of carbohydrate that is produced, measurement of absorbed PAR is expected to provide an estimation of gross photosynthesis. On the other hand, plants respire to maintain their metabolism and growth. This process depends strongly on environmental conditions such as temperature, and it requires carbohydrates assimilated from photosynthesis to generate energy (Thornley and Johnson, 1990). In general, canopy architecture is complex and leads to shadows with irregular shapes which are difficult to model analytically. However, such a system can be simplified by assuming the canopy to be of a simple shape.

The Beer-Lambert equation describes how light is attenuated through a material, which depends of the path length, h, and the light extinction coefficient, k. This relationship is given by:

$$I_h = I_0 e^{-kh} \tag{1}$$

where I_0 is the incident light intensity falling on the outer layer of the material and I_h is the light intensity after it is transmitted by a distance h through the material. In the context of this study the material is the tree canopy and h is depth of the canopy. An empirical relation developed by Campbell (1986) can be used to obtain k as a function of zenith angle θ and leaf angle distribution parameter x, i.e.,

$$k = \frac{\sqrt{x^2 + \tan \theta^2}}{x + 1.744(x + 1.182)^{-0.733}} \tag{2}$$

The leaf distribution parameter x is the ratio between the horizontal and vertical axis of the spheroid described by the leaf angle distribution of the canopy (Decagon Devices, 2008). Often its value is assumed to be 1, which corresponds to a spherical canopy distribution (Zarate-Valdez et. al., 2012).

An empirical model, given below, was developed by Rojo et. al. (2014) to describe diurnal PAR interception (U_t) as a function of zenith angle (θ) and midday PAR interception (U_n):

$$U_t = U_n(t) * \frac{F_t}{F_n}(\theta) \tag{3}$$

where F_t and F_n are the PAR components of the incident radiation (i.e. full sun) multiplied by the area covered by the shadow at time t and midday (solar noon),

respectively. The ratio F_t / F_n was found to be a function of zenith angle. Midday PAR intercepted data from a few days were used to develop an empirical curve which described midday PAR interception throughout the season (seasonal growth curve).

Net photosynthesis is the difference between the carbohydrates accumulated by the plant though photosynthesis and expended by plant respiration. The amount of net photosynthesis will determine the resources available for growth, i.e., yield, biomass, and storage. The rate of leaf photosynthesis as a function of incident light flux densities has been described by several authors as a rectangular hyperbola (Charles-Edwards and Glynn, 1986; Thornley and Johnson, 1990; Jones, 1992; Campbell, 1998; Koller and Upadhyaya, 2005, Boote et. al., 2013). The following equation from Charles-Edwards and Glynn (1986) describes the net photosynthesis rate of a leaf:

$$\frac{\partial}{\partial L}\left(\frac{\partial P_n^L}{\partial t}\right) = \frac{\gamma\, P_m\, I}{\gamma\, I + P_m} - R_D \tag{4}$$

where P_m (g/m^2/s) is the light saturated photosynthesis, γ is the quantum efficiency (g/J of CO_2), I (W/m^2) is the downward light flux density upon the leaf surface, R_D is the dark respiration rate (g/m^2/s), L is the leaf area index and P_n^L is the net photosynthesis of a leaf (g/m^2/s).

Light interception by the crop canopy given in equation (1) and the leaf photosynthesis concept presented in equation (4) can be combined to develop models of canopy photosynthesis (Thornley and Johnson, 1990). Equation (4) can be integrated over the entire light penetration path through the canopy to obtain an expression for photosynthesis per unit ground area as a function of the light interception (Charles-Edwards and Glynn, 1986; Thornley and Johnson, 1990; Koller and Upadhyaya, 2005). Integration of equation (4) results in the following equation:

$$\frac{dP_n^C}{dt} = \frac{\gamma\, P_{m0}\, I_0\left(1 - e^{-k\,LAI}\right)}{\gamma\, I_0\, k + P_{m0}} - R_c = \frac{\gamma\, P_{m0}\, Q}{\gamma\, I_0\, k + P_{m0}} - R_c \tag{5}$$

where P_{m0} (g/m^2/s) is the light saturated photosynthesis of an upper leaf, $Q = I_0(1 - e^{-kLAI})$ (W/m^2) is the light intercepted, R_c is the canopy dark respiration rate (g/m^2/s) and P_N^L is canopy net photosynthesis rate per unit ground area (g/m^2/s).

The objectives of this study were to: 1) Develop an analytical model to estimate daily PAR intercepted by a plant throughout a growing season based on just a few sets (preferably only one set) of light interception data obtained during the early part of the season. 2) Estimate potential yield of an individual tree or a block of trees using PAR interception data.

MATERIAL AND METHODS

A third generation canopy PAR interception system retrofitted on to a Kawasaki Mule was used to measure diurnal PAR interception in almond and walnut orchards. The PAR interception system consisted of 640 PAR sensors distributed along a bar (i.e. lightbar), which were divided into 16 measurement units with 40 sensors each. These units defined the spatial resolution of the system to be 40 centimeters. These sensors were sensitive to incident radiation in the 400-

700 nm range in which chlorophyll is also sensitive (i.e. PAR range). In addition, a rotary encoder was connected to the driveshaft of the Kawasaki mule to record distance travelled. A differential GPS was also included in the system. All data were recorded using a Campbell Scientific CR3000 data acquisition system at a rate of 10 Hz. Lightbar system is shown in figure 1.

Movement of the sun leads to a large variation in the shadow cast by an object from sunrise to solar noon (decreasing shadow) and from noon to sunset (increasing shadow). Since PAR absorption from a given tree is closely related to the shadow it casts, it was necessary to consider the size of the shadow of a tree of interest at any time. In order to collect shadow data of a specific tree through the day it was necessary to develop a methodology that allowed us to distinguish between sensors located under the shadow of that tree and that from trees in a neighboring row. This is especially important in the analysis of diurnal data, as sensors that contribute to a given tree's shadow change with time.

A Matlab script was developed to process PAR data, to generate maps of both sides of the row, and to further divide the row into blocks. A virtual grid was generated for this purpose with a pixel size of 40 X 40 cm^2 (i.e. spatial resolution of the lightbar system). GPS coordinates were used to localize the starting point at each end of the row, where multipath errors were low. UTM coordinates were rotated to create a row-based local coordinate system where only 1-D distance information along the crop row was needed. Encoder data was used to assign each PAR data point to pixels located in the virtual grid points on the ground. When multiple measurements were located inside a pixel, an average value was used.

Fig. 1. Lightbar system mounted on a Kawasaki mule.

To incorporate PAR information from both sides of the row, two scans obtained from the travel of the lightbar device in opposite directions in adjacent rows were used. If the respective data corresponding to two sides did not match perfectly, visual correction was employed to match them. Since the lightbar system could not obtain the light interception data where the tree trunks were located, a spline curve fitting technique was used to estimate the value of the central pixel.

After the map was created, the PAR intercepted by trees in each block formed by "n" number of pixels was obtained using the following formula:

$$U_t = \sum_{i=1}^{n} \left(I_{FS} - I_i \right) \Delta A \qquad (7)$$

where I_{FS} is PAR received at the top of the tree (i.e. data collected in the full sun), I_i is PAR received at the bottom of the tree by the ith pixel in the shadow, ΔA is the pixel area and U_t is the total amount of PAR intercepted by a block of five trees.

PAR intercepted by trees is needed to calculate net photosynthesis by equation 5. Our goal was to use one or a few measurements from the lightbar system to estimate the overall PAR intercepted over the whole season. Two models, one analytical and the other empirical, were compared. The empirical model is described by Rojo et. al. (2014). Solar noon scans were collected in Nickels Soil Laboratory, Arbuckle, CA during the 2012 and 2013 growing seasons. Diurnal scans were also collected during the 2012 season and were used to validate the models. The scans involved two rows of almonds containing 10 blocks of five trees each, and two rows of walnut containing 8 blocks of five trees each.

An analytical model was developed to estimate PAR interception, where the canopy shape, size and density were estimated by an early season lightbar scan. The model considered row spacing, tree spacing within the row, latitude and longitude of the orchard, day of the year, time of the day, and orientation of the row. The model assumed a spherical canopy over a flat surface. Under these assumptions the shadow is an ellipse with one of its semi-axis a constant and the other a function of the Zenith angle. The model that estimates the size, position, orientation and intensity of the shadows at any time is obtained as follows:

Figure 1 shows the 2-dimensional representation of the problem, where the canopy is represented by a circle. Only one semi-axis of the shadow can be seen in the diagram, which corresponds to the length of the shadow (L). The diagram is aligned with the azimuth angle (i.e. the vertical plane that contains the center of the sun and the central leader of the tree), where the canopy shadow and sun are always located on opposite sides. The shadow orientation angle (i.e. orientation of the major semi-axis of the shadow with the meridian passing through the location) is obtained by: $\rho = \sigma + 180$, where σ is the azimuth angle and ρ the shadow orientation angle.
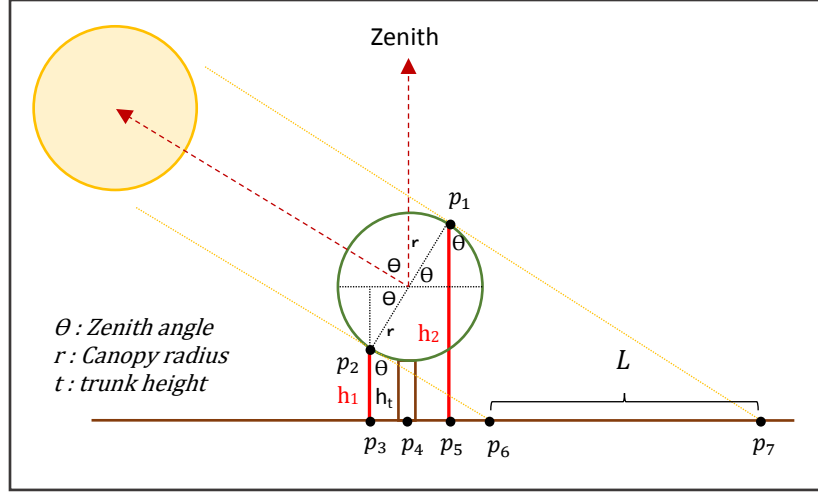
Figure 2. Diagram of a spherical canopy projected in two dimensions.

The length and position of the shadows were calculated using two points on the canopy's outer boundary that are tangent to the sun's rays (i.e. p_1 and p_2). The height of those points are represented by h_1 and h_2 (figure 2). If we only focus on h_1 and h_2 as if they were two vertical poles placed on the ground, their shadows can be calculated based on the zenith angle (θ), the canopy radius (r) and the trunk height (h_t). The shadows of length L_1 and L_2 cast by vertical poles of lengths h_1 and h_2 are given by:

$$L_1 = \frac{h_1}{\tan(90-\theta)} = \frac{h_t + r - r\sin\theta}{\tan(90-\theta)} \tag{8}$$

$$L_2 = \frac{h_2}{\tan(90-\theta)} = \frac{h_t + r + r\sin\theta}{\tan(90-\theta)} \tag{9}$$

If we define p_4 as the center point in a local coordinate system, then the position of the shadow with respect to the center of the tree can be obtained. The distances between the points p_4 and p_6 (d_{4-6}), and the points p_4 and p_7 (d_{4-7}) are:

$$d_{4-6} = L_1 - r\cos\theta \tag{10}$$

$$d_{4-7} = L_2 + r\cos\theta \tag{11}$$

The difference between the equations (10) and (11) is the length of the shadow, L.

$$L = \frac{2r[\sin\theta + \cos\theta\tan(90-\theta)]}{\tan(90-\theta)} \tag{12}$$

Finally, the position of the center of the shadow in the local coordinate system with p_4 as the origin is computed by:

$$p_x = \left(d_{4-6} + \frac{L}{2}\right)\sin\rho \tag{13}$$

$$p_y = \left(d_{4-6} + \frac{L}{2}\right)\cos\rho \tag{14}$$

where the positions p_x and p_y are the east-west and north-south components respectively. The height of the trunk was assumed to be 0.8 meters. The area of the ellipse that describes the shadow of the tree for the spherical canopy case is:

$$S = \pi \left(L/2 \right) r \tag{15}$$

where $L/2$ and r correspond to the semi major and minor axis of the ellipse, respectively. Notice that the major axis changes during the day while the minor axis remains constant. If the assumptions about the canopy shape and flatness of the orchard surface were reasonable, we could replace the value of S in equation (15) by its real value (i.e. the area of the shadow measured by the lightbar system) and obtain the radius of the canopy by solving for r.

The shading effect of neighboring trees was incorporated by using equations (12), (13) and (14) by considering the interaction of nine adjacent trees simultaneously as shown in figure 3. In this figure L, B, and W represent the length of the shadow, the row spacing, and the tree spacing within the row, respectively and (γ) is the row orientation.

After the dimensions, position, and orientation of the shadows have been computed, the energy available for the tree (F_0) can be estimated. However, additional information about how the light is being attenuated through the canopy is required to estimate how much of the energy available will be transmitted, absorbed, and reflected. For canopies the proportion of energy reflected is small compared to the amount being transmitted or absorbed. Reflected and absorbed energy are considered together as the amount of energy being intercepted by the canopy. Equation (1) can be slightly modified to compute PAR intercepted by the canopy as follows:

$$U_t = F_0 \left(1 - e^{-kh} \right) \tag{16}$$

where U_t is the amount of PAR intercepted by unit area. The proportion of PAR being intercepted by the canopies (i.e. U_t/F_0) can be measured by the lightbar system and k can be obtained by equation 2. Then, equation 16 can be used to obtain the depth h (which is also known as the leaf area index) that is assumed to be constant during the day. If a growth curve (seasonal PAR interception curve) is used to computed U_t, this procedure can be used to calculate h for each day, otherwise a constant growth condition can be assumed where the same U_t is used for the entire season.
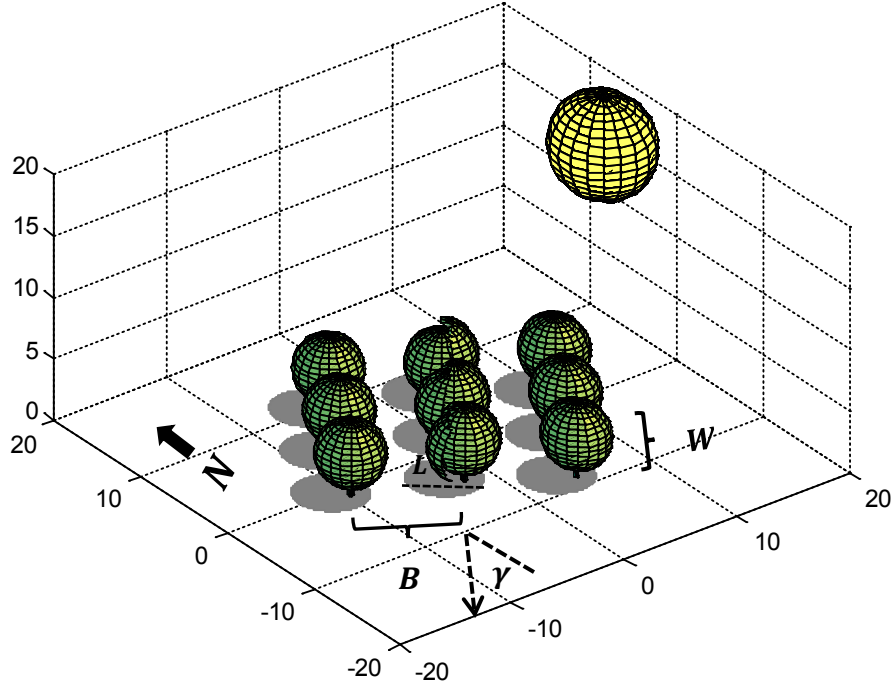
Figure 3. Example of a typical display for nine trees with their respective shadows.

A model developed by Hottel (1976) was used to compute direct and diffuse components of the solar radiation at any time. The energy received by a tree, F_0, can be calculated multiplying the area of its shadow (equation 15) by the solar radiation in the PAR range, which is assumed to be half of the total solar radiation (Campbell, 1998).

To obtain the net photosynthesis accumulated through the season, equation 5 was integrated over the season and multiplied by the canopy projected area (A_p), which is πr^2 (for a block of five equally sized trees A_p is $5\pi r^2$). The rate of photosynthesis of a light-saturated leaf (unshaded), P_{m0}, and quantum efficiency, γ, were obtained from the literature (Rosati et. al., 2006). R_c was assumed to consist of maintenance and growth components, where the maintenance component was assumed to be proportional to the accumulated net photosynthesis and the growth component was assumed to be proportional to the rate of net photosynthesis, i.e.,

$$R_C = \mu \frac{dP_N}{dt} + b_0\, P_N \tag{17}$$

where μ and b_0 are proportionality constants, which describe growth and maintenance respiration, respectively.

Potential yield can be estimated using the conservation of mass approach, where net assimilation evaluated over the whole season can be equated to the sum of the masses of fruits (yield) and leaves. For deciduous plants, changes in the shoot and root mass are expected to be low compared to changes in leaf and fruit mass. In addition, stored carbohydrates from the previous year's reserve will also

contribute to yield and mass of leaves in the current season, and a portion of carbohydrates fixed during the current season will be stored for the next season.

$$Y = \xi\, P_n - l_m - \Delta RS \tag{18}$$

where P_n is the accumulated net photosynthesis throughout the season (equation 5), ξ is the dry mass conversion efficiency, l_m is the leaf mass on a dry basis, ΔRS is the increase in shoot and root mass during the current year compared to the previous year, and Y is the potential yield. The parameter ξ was assumed to be 0.68 as it corresponds to the amount of dry mass produced ($C_6H_{12}O_6$) to the amount of CO_2 assimilated. l_m can be approximated by:

$$l_m = \frac{W_L}{A_L}\left(A_P\, LAI\right) \tag{19}$$

where W_L and A_L are the weight (g/leaf) and area (m^2/leaf) of an average leaf respectively, LAI was obtained using the Beer-Lambert equation, and ΔRS is assumed to be zero. After harvesting almonds and walnuts, a trailer equipped with load cells was used to measure the yield of each block. A sample of 2 kg was taken per block and these samples were placed in a nut drier for five days to obtain dry weight of samples.

RESULTS AND DISCUSSION

A time series of PAR intercepted data for June 28th is shown in figure 4 as an example of the output obtained from the lightbar system after the data had been processed. It can be seen that shadows are longer in early morning and late afternoon hours and shorter at solar noon. Conversely, the intensities of the shadows are higher at midday and lower in early morning and late afternoon hours. As expected, shadows move from West to East.
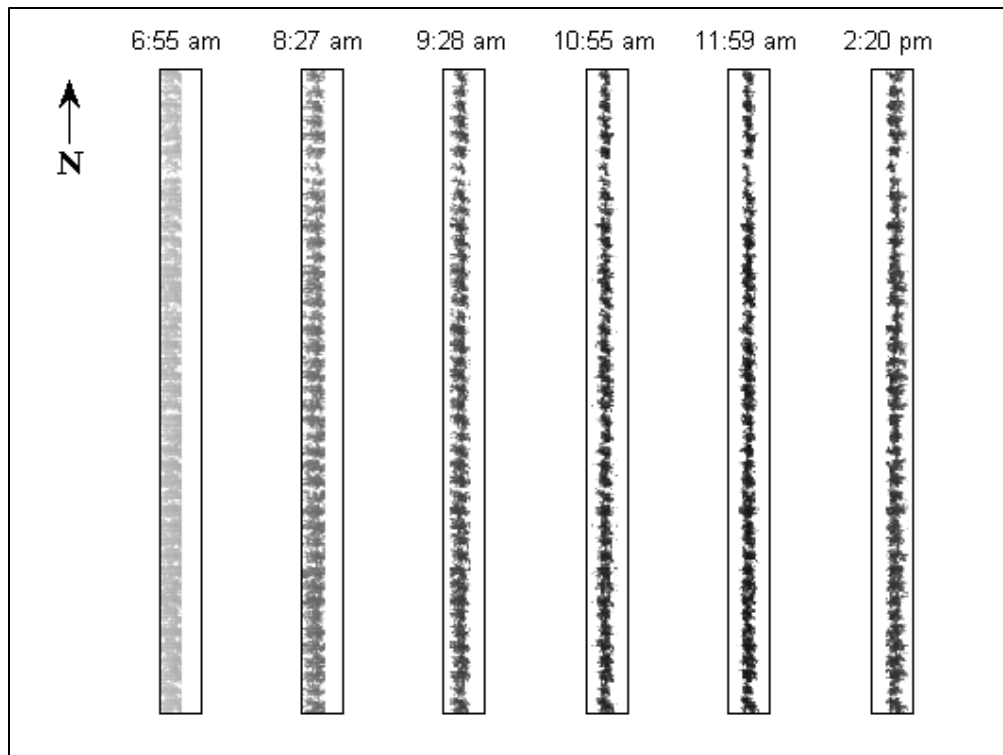
Fig. 4. Diurnal scans of PAR intercepted for a row of walnut trees on June 28th (solar time).

Seasonal changes in midday PAR intercepted by a block are due to changes in the environment (i.e., seasonal changes in the normal component of the solar radiation) and changes in the canopy (i.e., growth could increase the projected area or the canopy density or both). Midday PAR intercepted was found to increase exponentially during 2012 in both almond and walnut trees (left side figure 5), which differed from what we expected from the behavior of solar radiation (which is a sinusoid with a maximum on June 21th for clear sky conditions). This implies that during this period midday PAR interception was being more affected by the canopy growth than the solar radiation source. At the end of the season there was a drop in PAR interception which could be related to the decrease in solar radiation or to a loss of leaves after shaking.

During the 2013 season, midday PAR interception seemed to reach a plateau, where the growth rate seen in season 2012 is not present in either crop. The trees used in this study were still young and it seems that they were actively growing during 2012 season but their growth is being limited during 2013 season probably by the tree spacing of the orchard. The drop in PAR interception found at the end of 2012 season is also present at the end of 2013 season. Walnut trees presented higher values of midday PAR interception, with the only exception being the first walnut data of the 2013 season, which was taken when no leaves were present. Both the almond and walnut orchards were still filling in their allotted space.
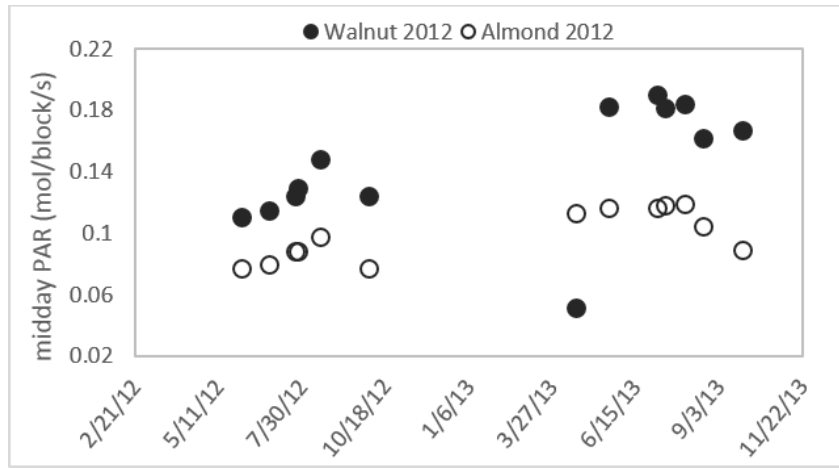
Fig. 5. Midday PAR interception for season 2012 and 2013 in almonds and walnut.

Diurnal and seasonal PAR intercepted were estimated by the analytical and empirical models for each block of five trees during the growing seasons of 2012 and 2013. A typical surface plot of PAR interception for one of the blocks is shown in figure 6, where the results of the analytical and the empirical models can be seen for growth and no-growth conditions.
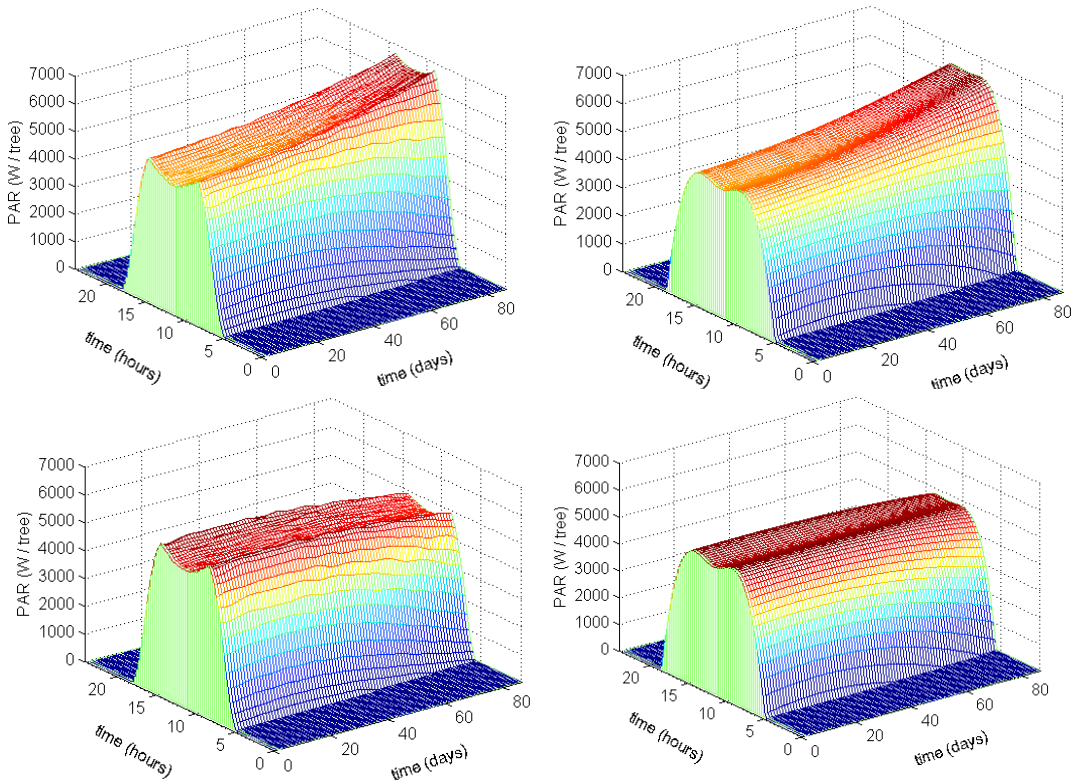

Fig. 6. A typical 3-D plot of the diurnal and seasonal PAR intercepted by an almond block. Left: analytical model, Right: empirical model, Top: with growth curve, Bottom: without growth curve. 2012 season.

In both models, PAR interception was found to be lower early in the morning and late in the afternoon and reached peak values slightly before and after solar noon. It is interesting that the PAR interception dipped slightly at solar noon and this phenomena, tended to decrease through the season. This feature can be explained by two phenomena acting together. First, the shadows are larger at sunrise and sunset, and decrease near solar noon, when the sun is almost directly above the canopy. Second, PAR intercepted per unit surface area was found to be higher at solar noon, and decreases as sun altitude decreases. This happens because the radiation transmitted is concentrated over a smaller projected area (i.e., shadows are smaller) at midday and the incident solar radiation has its higher values at solar noon (Hottel, 1976). Since the PAR intercepted by a tree or a block of trees is the product of intensity of radiation and the shadow size, we see a slight decrease in the PAR intercepted at solar noon as the decrease in the shadow size near noon more than compensates for the increase in the incident radiation at that time.

At the bottom of figure 6, we see seasonal PAR interception for the no-growth condition of the 2013 season, where midday PAR interception depends only on sun elevation. The no-growth condition has the advantage over the growth condition that only one field visit is required with the lightbar system, whereas in the growth condition a growth curve has to be generated by visiting the orchard multiple times.
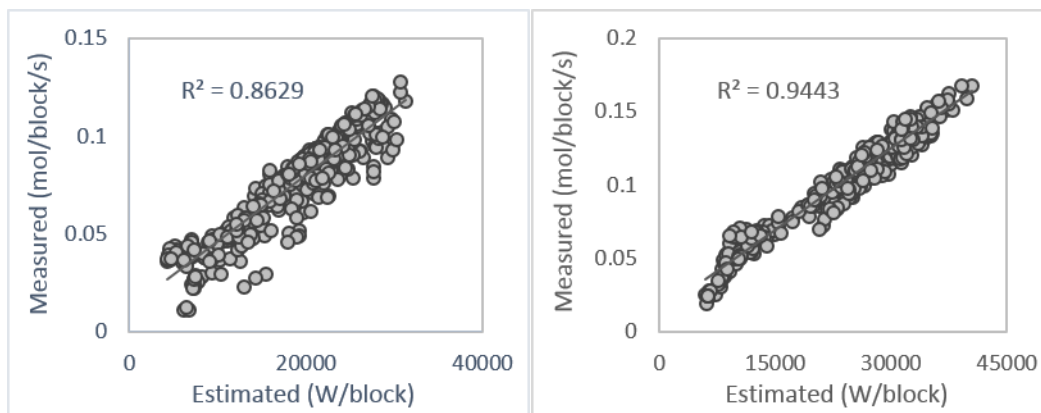

Fig. 7. Validation of the analytical model for almond (left) and walnut (right) trees.

Estimated versus measured data from June 28th 2012 was used to validate the analytical model of PAR interception (figure 7). Coefficient of determination (r^2) values of 0.86 and 0.94 were found for almond and walnut trees, respectively. The empirical model was validated by Rojo et. al. (2014) and they found coefficients of determination (r^2) of 0.89 and 0.93 for almond and walnut trees respectively. This indicates that PAR intercepted at any time can be estimated using both prediction techniques.

In figures 8 and 9, both potential and actual yield as functions of midday PAR interception are shown for the 2012 and 2013 seasons. The yield from those

trees with lower absolute midday PAR intercepted are closer to their respective potential yields than those with higher PAR interception values. Real yield had an average and coefficient of variation of (24.3 $\pm$ 0.26) kg/tree for almond trees and (46.47 $\pm$ 0.34) kg/tree for walnut trees. While these results should be examined further and all relevant assumptions carefully reviewed, it is possible that uniform management of the orchard could be a reason for the observed results. These results appear to indicate a need for plant-specific input management based on potential yield of individual trees.
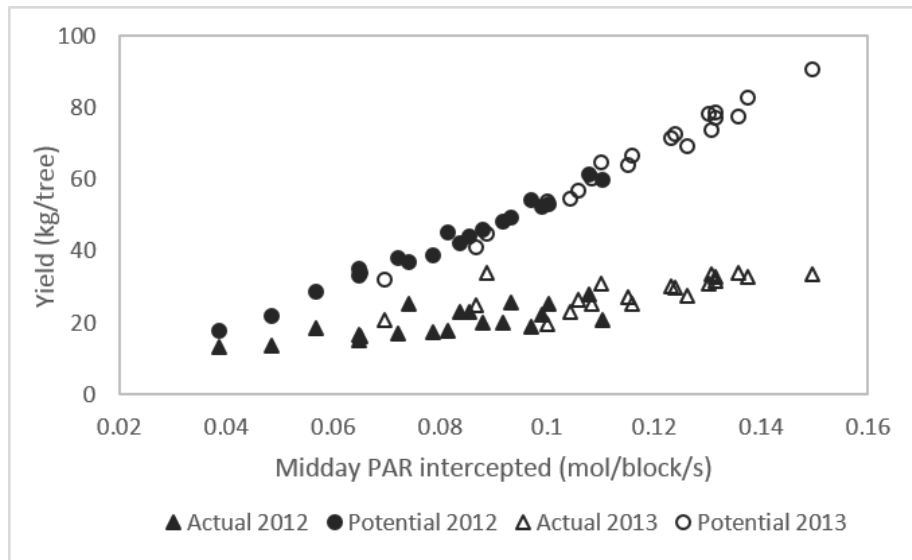

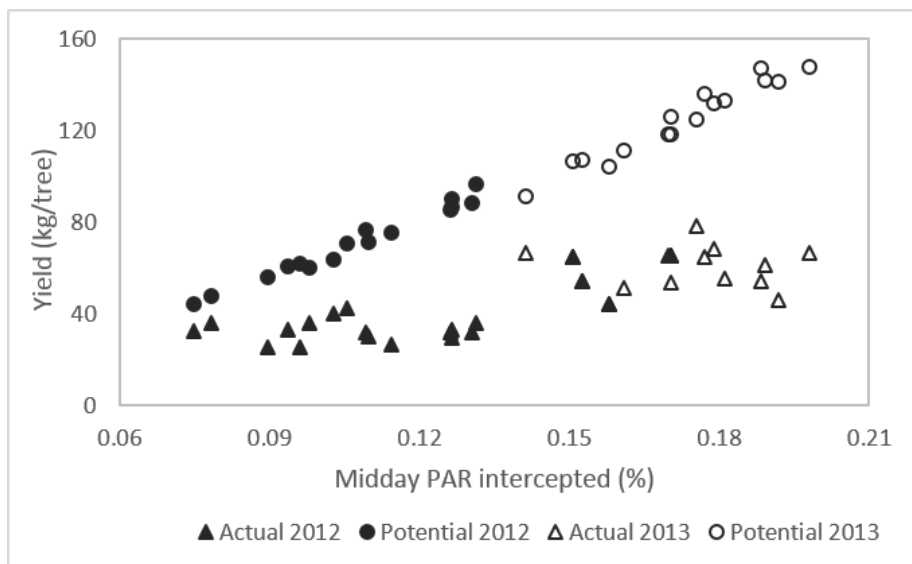**Fig. 8. Potential and actual yield versus PAR intercepted at noon in almond trees.**

Fig.9. Potential and actual yield versus PAR intercepted at noon in walnut trees.

Actual and potential yields were found to depend on the absolute midday PAR interception during a reference day (June 28th for 2012 data and May 20th for 2013 data). Absolute values of PAR interception (U_t) were found to have a better correlation with yield (actual and potential) than the relative PAR interception $\left(U_t/F_o = \left(I_t A_p\right)/\left(I_0 A_p\right)\right)$, where the effect of the area projected has been removed. The coefficient of determination (r^2) values for the relationship between actual yield and absolute midday PAR intercepted over the course of both seasons was 0.81 and 0.63 for almond and walnut crops, respectively.

Due to the growth found during the 2012 season, the trees were able to intercept more PAR during the 2013 season (figure 5). As a result, greater potential and actual yields were found in both the almond and walnut crops for the 2013 season (figures 8 and 9). The coefficient of determination (r^2) values for the relationship between actual and potential yield was 0.80 and 0.59 for almond and walnut crops, respectively.

CONCLUSIONS

The results for the 2012 and 2013 seasons showed that the total amount of PAR intercepted by a block of five trees at any time during the day can be found analytically using one lightbar scan, early in the season, as a reference to estimate the radius of the canopy and its optical density. A good correlation was found between measured values of PAR intercepted and estimated values of PAR intercepted. Moreover, a comparison between PAR interception data estimated analytically and empirically showed that both approaches had a similar behavior over the season.

A good correlation was also found between yield (for both actual and potential) and absolute midday PAR intercepted, and between actual and potential yield for both almond and walnut trees. Moreover, the actual yield from those blocks with lower absolute midday PAR intercepted was closer to their respective potential yield than those with higher absolute PAR intercepted. This result indicates that there is a potential to use spatially variable PAR interception data to implement site-specific input management and enhance production.

These results are considered only preliminary and changes will have to be made to incorporate actual measured parameters instead of using the values collected from the literature, especially for variables such as P_{m0} and γ in the photosynthesis model. In addition, better representation of the respiration term and better accounting of energy consumed in producing new shoots to support crop canopy may improve predictive ability.

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