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Evaluation of Digital Hemispherical Photography and Plant Canopy Analyser for Measuring Vegetation Area Index of Orange Orchards

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Abstract: This study presents the results of an evaluation of two indirect methods (Plant Canopy Analyser (PCA) and hemispherical photographs) for measuring vegetation area index VAI of two orange orchards, differing by their ground fraction cover (f_c). The evaluation is based on reference data obtained by destructive measurements on limited samples, which allow to calibrate and validate an exponential relationship between the diameter of branches and associated areas of leaves ($R^2 = 0.99$). The obtained results show that the two indirect methods underestimate the reference values of VAI. For the PCA device, the best estimates of VAI are obtained using the five rings for high f_c ($f_c = 0.7$) and using only four rings for low f_c ($f_c = 0.3$). For both case, the hemispherical photographs give accurate estimates of VAI: the relative errors are about 11 and 14% for high and low f_c, respectively. Alternatively, a simple method consisting of calculating VAI as the weighted average of the maximum (VAI_{max}, below the tree) and minimum (VAI_{min}, at the center of four trees) values using f_c as a weighting factor, was successfully tested ($R^2 = 0.90$). For both indirect methods, the tree volumes are well estimated with comparison to the values calculated assuming an ellipsoidal form.

Key words: Vegetation area index, hemispherical photos, LAI-2000, orange

INTRODUCTION

Leaf Area Index (LAI) is the main determinant of light interception and thus of canopy assimilation and transpiration. The LAI measurements can be made using two categories of methods: direct and indirect (Chason *et al*., 1991; Fassnacht *et al*., 1994; Sonnentag *et al*., 2007). The first one is generally destructive and widely used for annual species. In this case, the distribution of the leaf area in field crops is more homogeneous than in arrays of trees. When applied to large trees, direct methods are extremely difficult, expensive and often not feasible. Alternatively, indirect methods for LAI measurements based on the transmittance of radiation through the vegetation have been developed.

Among several, Plant Canopy Analyser (PCA) (LAI, 2000) and the Hemispherical Photographs (HP) have shown a good performance, especially for the homogenous vegetation (Wells and Norman, 1991; Englund *et al*., 2000; Cescatti, 2007). An important error can be common when there are large gaps within the vegetation or when the leaves are not arranged randomly (Jonckheere *et al*., 2004).

In the Mediterranean regions, citrus are one of the main components of agricultural systems in many semi-arid areas and cover more than 10^6 ha (Rana *et al*., 2005). As far as we know, no measurements of LAI in orange tree orchards have been reported yet, despite the importance of LAI data in understanding the physiological responses of orange to water supply and radiation. Orange trees are usually grown in regular patterns with tree spacing between 3 and 7 m. Many other tree species are also grown as widely spaced orchards. The use of indirect methods to determine LAI is not straightforward as large gaps will be present (Villalobos *et al*., 1995). Alternatively, when the trees are small and/or sufficiently spaced, the plantation can be treated as the sum of the isolated trees (Lang and McMurtrie, 1992; Villalobos *et al*., 1995).

The objective of this study is to evaluate the use of the LAI-2000 and hemispherical photographs to measure LAI and tree volumes in two orange orchards differing by their plant densities.

MATERIALS AND METHODS

Orange orchards: Measurements are made in two orange orchards (mandarin, Var. Nour) of the Saada domain

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(Saada 1 and Saada 2), located at 15 km to the west of the Marrakech City, Morocco. Measurements are conducted in March 2004 and April 2005 for Saada 1 and Saada 2, respectively. In Saada 1, the trees are spaced at 3.5×5 m. The height and maximum radios of tree crown are 3.15±0.19 m and 1.85±0.13 m, respectively. In Saada 2 site, the tree size is relatively more heterogeneous. These characteristics are 7×7 m, 3.27±0.71 m and 2.15±0.48 m, respectively. The ground fraction covers (f_c) of the two sites are then about 0.7 and 0.3, respectively. The pruning practices lead to a particular canopy of trees; they have an ellipsoidal shape with a feeble leaves density in vertical tree axis; so that all tree leaves potentially contribute to the light interception. In both sites, the tree rows are oriented Eastwest. A full description of both sites can be found by Er-Raki *et al.* (2009) and Ezzahar *et al.* (2009).

Vegetation area index measurements

Indirect measurements: As the PCA and HP estimates refer to the surface areas of all the phytoelements (leaves and steams), the term Vegetation Area Index (VAI) will be used instead of LAI, which refers only to the green leaves. Measurements of both methods refer to the canopy light interception. The PCA measures gap fraction (transmittance) by comparing diffuse readings above and below the canopy at five zenith angles (7, 23, 38, 53 and 68°). For both readings, the sensor is looking up at the sky.

Digital images were analyzed using CAN Eye software (http://www.avignon.inra.fr/can_eye). All images were first converted to gray scale (256 levels) and then to binary (black and white pixels) using an interactive manual threshold: the user decides which grays should be converted to black (vegetation) and which should be converted to white (sky). The fraction of the sky pixels represents the canopy gap fraction. In order to compare the results of both indirect methods, digital images were also subdivided into five concentric rings (0-13°, 16-28°, 32-43°, 47-58° and 61-74°). For each photo or PCA measurements, VAI may be calculated as (Wells and Norman, 1991):

$$\mathrm{VAI} = -2\int_0^{\pi/2} \ln T(\theta) \sin\theta \cos\theta \, d\theta \qquad (1)$$

where, $T(\theta)$ is the gap fraction at a given zenith angle θ. The method of Welles and Norman (1991) uses the rectangular rule to integrate Eq. 1 for the five zenith angles corresponding to the rings of PCA.

The two indirect methods, described above, are used to measure VAI of two orange orchards. The material used are LAI-2000 (Plant Canopy Analyser, Lincoln, Nebraska, USA) and Nikon Coolpix 4500® with a FC-E8 fish-eye lens converter. Two appropriate experimental protocols were applied in this study. The first one is relative to the high tree density (Saada 1) and the second one is for the low tree density (Saada 2) (Manual of LAI- 2000) (Fig. 1). In Fig. 1, black points refer to the position at soil level where the measurements were taken. The sensors are directed upwards and measurements are made in absence of the direct radiation; immediately after sunset.

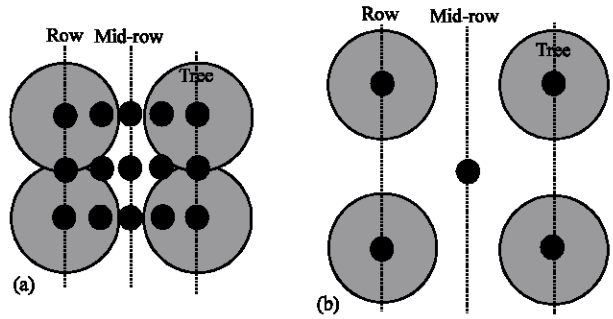

Fig. 1: Position of vegetation area index measurements (black points) with plant canopy analyser LAI-2000 and hemispherical photograph. (a) Saada 1, with high ground cover f_c = 0.7 and (b) Saada 2, with low ground cover f_c = 0.3

In Saada 1 site, measurements were taken in sample area covered by 3×5 trees. In each point (Fig. 1a), two PCA readings are made using a 180° view cap; in the opposite mid-surface of the sensor. Also, the analysis of the hemispherical photos was made after applying a mask of 180° to have similar views as PCA readings.

In Saada 2 site, measurements were taken in representative area covered by 3×7 trees. In this site, trees are largely spaced and therefore VAI can be obtained only by measurements below the crown (next to the trunk) (Fig. 1b); using C2000 software (Manual of LAI-2000). Thus, under tree crown, four PCA readings were taken using a 90° view cap and oriented along the tree grid diagonals; Eastnorth, Northwest, Westsouth and Southeast (measurements were not affected by neighboring trees). Also, the hemispherical photos, taken below the crown, were analyzed by applying a mask of 270°, placed in the diagonal directions of the tree's grid.

In addition, the same measurements taken in Saada 1 were also made in each point in Saada 2 (Fig. 1b). The obtained VAI values will be used to test the model proposed below (Eq. 2). An alternative method consisting of calculating VAI as a linear function of the maximum (VAI_{max}; below the tree) and minimum (VAI_{min}; center of the tree's grid) was also tested:

$$\mathrm{VAI} = \alpha \mathrm{VAI}_{max} + (1-\alpha)\mathrm{VAI}_{min} \qquad (2)$$

where, α is an empirical coefficient. Each tree's grid have one value of the couple (VAI_{max}, VAI_{min}), where VAI_{max} is the average of VAI measured below the four trees of the same grid.

Direct measurements: Direct measurements are made on 31 and 32 branches, respectively for Saada 1 and 2, with different diameters chosen from those pruned (from the rows used in the indirect measurements). The selected branches were separated into leaves, steam and trunk. Total fresh weight of each component was measured in an electronic scale. Subsamples were taken to determine their area and dry weight. The surface area of steams and the trunks were estimated from their dimensions assuming cylindrical form (i.e., length times width times $\pi/2$). The specific area of each element was estimated as the ratio area/weight. Then the total area corresponding to each element was calculated as dry weight times specific area. The obtained results will be used to determine relationships between branch leaf area (L_A), steam and trunk area and branch diameter (d). Finally, these relationships will be used to calculate the values of LAI and VAI using simple measures of the diameters of each tree branches.

Tree volumes estimates: The second important parameter estimated by PCA and HP is the leaf area density LAD, following the method proposed by Welles and Norman (1991). These methods give only one LAD value for each tree. However, in present case this parameter was very heterogeneous in each tree crown. For example, for a volume of 20×20×20 cm^3 the LAD varied from 0 to 8.5 m^2 m^{-3}. Thus, the method of Welles and Norman (1991) is proposed here to estimate Tree Volume (TV) rather than LAD, knowing that the latter is the plant area/TV.

In the integrated software in the PCA, TV is calculated from the coordinates of the tree silhouette. The tree projection was divided in trapezoids which were revolved about the vertical axis. The volumes corresponding to the revolution of each trapezoid were calculated using the second Pappus-Guldinus theorem (Selby, 1975; Villalobos *et al*., 1995) and summed to obtain the tree volume. This method was generally used to calculate TV and therefore LAD for isolated tree or for tree orchard with a low tree density (Manual of LAI-2000). The coordinate (X,Y) of tree silhouette was measured by placing vertically a large rule (in Eastnorth, Northwest, Westsouth and Southeast) and determining visually the intercept of the foliage with the ruler. The observer stayed at least 10 m from the tree under measurement. Alternatively, tree volumes were calculated assuming an ellipsoidal form as:

$$TV = \frac{4}{3}\pi abc \quad (3)$$

where, a, b and c are the semi-axis in the Eastnorth_Westsouth, Northwest_Southeast and vertical direction, respectively. The axis were taken as the maximum dimensions of the tree in each direction.

RESULTS AND DISCUSSION

Allometric relationships: The obtained relationships between the branch leaf area L_A (m^2) and its diameter d (m) are presented in Fig. 2 and given by the following exponential expressions:

$$L_A = 1.15\ e^{28.87d}\ R^2 = 0.94\ \ n = 21\ (\text{Saada1}) \quad (4)$$

$$L_A = 1.51 e^{24.97d}\ R^2 = 0.96\ \ n = 22\ (\text{Saada 2}) \quad (5)$$

where, n is the number of the branches used. These relationship trends are consistent with those obtained for the orange (Daamen *et al*., 1999; Rana *et al*., 2005), olive (Testi *et al*., 2004) and corn (Bethenod *et al*., 2000). However, the constants values are widely different. They reflect the effect of crop nature, variety and cultivation

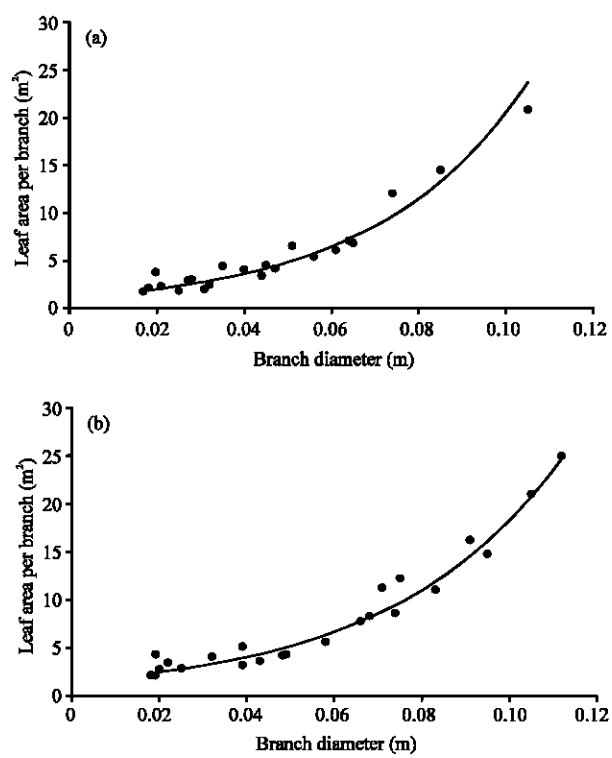

Fig. 2: Relationship between the branch leaf area (L_A) and its diameter (d) measured on 21 and 22 branches, for (a) Saada 1 and (b) Saada 2, respectively, after the experiment

practices (Villalobos *et al*., 1995; Jonckheere *et al*., 2004). The statistical analysis fitting χ^2 of Pearson (Dagnelie, 1992) shows no significant difference between the two obtained relationships, (Eq. 4, 5) ($p<5\%$). These relations are presented here separately because generally they are known to be more influenced by the variety and the crop management; especially pruning practices (Villalobos *et al*., 1995). The validity of these relations are tested against the remainder data (n =10 for both sites Saada 1 and 2). A good agreement between the calculated and measured L_A was observed:

$$L_{Ames} = 0.95 L_{Acal} + 0.19 \quad (R^2 = 0.99) \tag{6}$$

The slop and R^2 are close to 1 and the intercept is close to 0. The branch leaf area was also correlated to the surface area of steam and trunk S_A, the obtained relations are:

$$S_A = 0.07\, L_A \quad R^2 = 0.98 \quad n = 31 \text{ (Saada1)} \tag{7}$$

$$S_A = 0.09 L_A \; R^2 = 0.99 \quad n = 32 \text{ (Saada 2)} \tag{8}$$

Thus, the contribution of steam and trunk to VAI is less than 7 and 9% for Saada 1 and 2, respectively. However, the use of the indirect methods and even of the direct methods, for the VAI estimates in tree plantations, is associated with a possible large errors (Jonckheere *et al*., 2004), which reaches 30-40%. Thus, the difference between VAI and LAI can be considered negligible. Consequently, it can be concluded that PCA and HP estimates, which refer to the surface areas of all the phytoelements, are similar to LAI values.

The relationships between L_A, S_A and d (Eq. 4-5, 7-8) are used to obtain the trees VAI and therefore, the average VAI_{mes}, referred as measured vegetation area index.

Comparison between direct and indirect measurements of VAI: Table 1 presents the measured values of Vegetation Area Index (VAI_{mes}) and those estimated using LAI-2000 and HP (VAI_{est}) using 3, 4 and 5 rings. It should be noted that for both sites, the two used methods underestimate the measured values of VAI for the three cases of rings number. These offsetting errors may be common, such as when leaves are grouped along stems (increasing light transmittance). This result was consistent with other studies (Hale and Edwards, 2002; Jonckheere *et al*., 2004). However, the better estimates of VAI are obtained using the five rings for Saada 1 ($f_c = 0.7$) and using only four rings for Saada 2 ($f_c = 0.3$). The low

Table 1: Comparison between the values of VAI_{mes} from direct measurements and those of VAI_{est} estimated using LAI-2000 and hemispherical photographs

Site	Technique	Ring's number	VAI_{est}	VAI_{mes}
Saada 1	Photos (HP)	3	1.93±0.32*	3.2±0.29
		4	2.65±0.25	
		5	2.83±0.19	
	LAI-2000 (PCA)	3	2.10±0.23	
		4	2.41±0.27	
		5	2.67±0.22	
Saada 2	Photos (HP)	3	0.85±0.14	1.18±0.21
		4	1.01±0.14	
		5	0.86±0.12	
	LAI-2000 (PCA)	3	0.84±0.09	
		4	0.96±0.12	
		5	0.85±0.13	

Data are expressed as Mean±SE

tree density in Saada 2 leads to a high penetration of light through the ring 5 (zenith angle between 61 and 74°) to the ground under the crown. The transmittance measured, by PCA or HP, through this ring was frequently close to 1.

For both sites, the hemispherical photographs give the accurate estimate of the VAI; the relative errors are about 11 and 14% for Saada 1 and 2, respectively. These performances are well appreciated when compared them to those made by this technique in other tree plantations (Jonckheere *et al*., 2004).

The relatively high underestimation of VAI values by PCA is related to the fact that the PCA receives the scattering light by vegetation in addition to the diffuse radiation coming directly from the sky. The transmittance measured by the LAI-2000 was generally higher than the actual one (Wells and Norman, 1991).

Alternative method: The alternative method of estimating VAI as a linear function of maximum and minimum VAI (Eq. 2) was tested by calculating the α coefficient from the values of VAI, VAI_{max} and VAI_{min} relative to each grid used (10 and 12 for Saada 1 and 2, respectively). The α coefficient increased with tree radius and was very close to the fraction of ground cover f_c. Thus, a simple method to calculate VAI may be proposed as:

$$VAI = f_c\, VAI_{max} + (1 - f_c)\, VAI_{min} \tag{9}$$

Which produced VAI estimates very close to the measured values (Fig. 3); the regression equations are not different from X=Y. These results indicate that accurate measurements of VAI in orange orchards may be obtained by taking two measurements (highest and lower values) and weighting according to ground cover f_c. The latter may be easily derived from multispectral vegetation indices obtained by remote sensing.

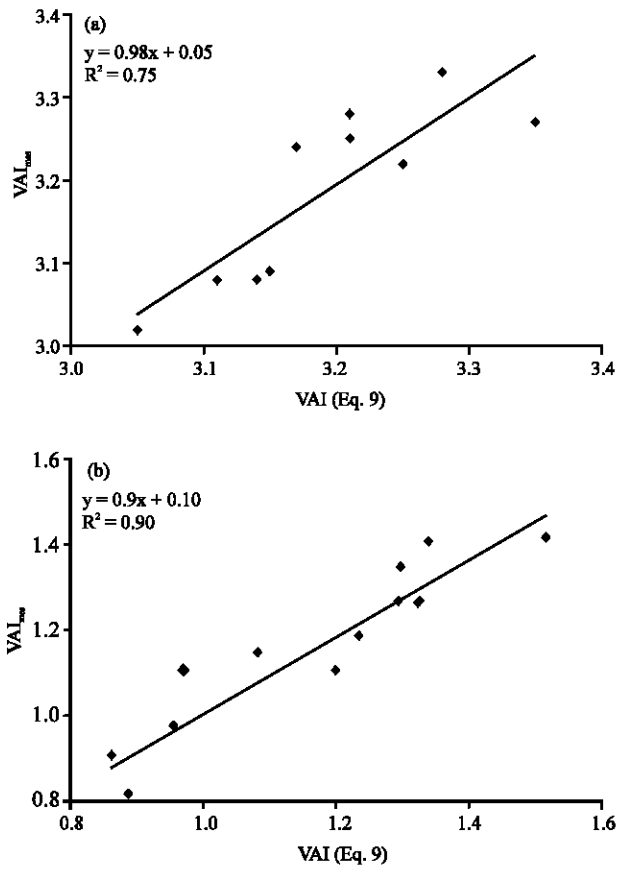

Fig. 3: Comparison between the measured and estimated values of VAI in (a) Saada 1 and (b) Saada 2. Estimations were made using the linear function of maximum and minimum VAI (Eq. 9)

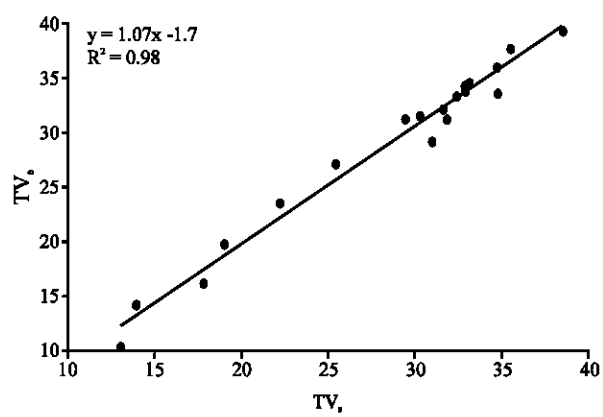

Fig. 4: Comparison between estimated tree volumes from the coordinates of the tree silhouette (TS_S) and estimates of tree volumes assuming an ellipsoid (TV_e)

Tree volumes: The validation of tree volume estimates from the coordinates of the tree silhouette $_{TVS}$ (second Pappus-Guldinus theorem, Selby, 1975) was made using only the data of Saada 2. The calculated values of $_{TVS}$ were between 10.4 and 39.3 m^3 $plant^{-1}$. Estimates of tree volumes assuming an ellipsoid TV_e were in very close agreement with those obtained from the silhouette (Fig. 4); the linear regression equation is not statistically different from the x = y and R^2 is close to 1. If the vertical axis of the ellipsoid (parameter c in Eq. 3) is taken as the crown length at the center of the tree, then the tree volume is underestimated by about 14.6% and $R^2 = 0.89$.

Tree volumes TV_e (m^3) were linearly related to the crown radios CR (m). The linear regression equation obtained for Saada 2 was

$$TV_e = 26.55CR - 27.28 \quad R^2 = 0.95 \quad n = 20 \qquad (10)$$

Crown radios have been used to estimate leaf area index, tree leaf area or tree biomass (Marshall and Waring, 1986; Chason *et al.*, 1991). In the last years, with the large expansion of the use of the optical remote sensing, this kind of relation (Eq. 10) was widely used (Johnson *et al.*, 2003). However, it could be depend on pruning practices, thus it should be used with caution to estimate the TV or other parameters.

CONCLUSION

Two indirect methods (plant canopy analyser PCA and hemispherical photograph), for determining the vegetation area index VAI of range orchards, were tested and compared. The results showed that the hemispherical photograph was the most accurate method for orchards with low and high green fraction cover. Additionally, a simple method calculating the orchard VAI, by combining the maximum (VAI below trees) and minimum (VAI at the center of the trees square), was presented and successfully tested.

The values obtained for VAI can be used to establish a 3D map of VAI and leaf area density, which constitute a tool to understand, explain and forecast the fluxes exchange between soil, plant and atmosphere of the orange orchards.

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