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Original article

Stand biometry and leaf area distribution in an old olive grove at Andria, southern Italy

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Abstract – The objectives of this paper were (1) to provide general biometry data for an 80-year-old olive (*Olea europea* L., cv. Coratina) grove in Andria, southern Italy, and (2) to compare different methods for estimating leaf area distributions. Stand biometry was represented by a stocking density of 132 trees ha^{-1}, mean spacing of 8.7 m and mean social area (proportional to spacing and tree size) of about 76 m^2 per tree. Trunk total circumference averaged 110 cm and after subtraction of missing or dead parts of stems averaged 81 cm, projected area of crowns averaged 17.7 m^2 and the mean tree height was 4.9 m. Leaf distribution was evaluated using calibrated ground-based side photographs through image analysis and through using a simple canopy-layer model (considering hollow volume within tree crowns) and double-Gaussian curves. The mean leaf size was about 5 cm^2 (distributed in a log-normal manner over the range of 2 to 12 cm^2). Considering whole tree crowns, the mean leaf density was about 2.6 m^2m^{-3}; the maximum leaf area occurred in canopy layers between 1.5 to 3 m, tailing with a steeper slope to the crown base and a less steep slope to the tree-top. The foliated volume of olive crowns (mean 33.2 m^3) contained on average 145 thousand leaves of the total area of 72.6 m^2. The corresponding leaf area index on the stand level (LAI_{grove} = 0.96), was rather low due to low stocking density. However when taking into account only the projected crown areas (and avoiding free space between trees), the mean LAI reached about 3.5 (range from 1–7). The radial pattern of leaf distribution derived from image analysis indicated peak LAI_{rad} values at a distance from the stem of about 60 to 70% of crown radius in trees of different size. The applicability of different approaches to the estimation of the necessary allometric parameters is discussed.

contour side photography / image analysis / geometrical modeling / vertical and radial leaf distribution / stem damage / crown form / biometry

Résumé – Dendrométrie et distribution de la surface foliaire dans une vieille oliveraie près d'Andria, dans le sud de l'Italie. L'objectif de ce travail a été d'obtenir des données biométriques générales pour une vieille oliveraie de 80 ans (*Olea europea* L., cv. Coratina) installée près d'Andria, dans le sud de l'Italie, et de comparer différentes méthodes d'estimation de la surface foliaire. L'oliveraie comportait 132 arbres à l'hectare avec un espacement moyen de 8,7 m et une surface sociale moyenne (proportionnelle à l'espacement et à la taille des arbres) d'environ 76 m^2par arbre. La circonférence des arbres atteignait en moyenne 110 cm et, après soustraction des disparus ou des parties mortes des troncs, elle atteignait en moyenne 81 cm. La surface projetée des couronnes atteignait en moyenne 17,7 m^2 et la hauteur moyenne des arbres était de 4,9 m. La distribution des feuilles a été évaluée en utilisant (i) un système de photographies à partir du sol suivies d'une analyse d'images, et (ii) un modèle simple de stratification de la canopée (en considérant un volume creux dans la couronne des arbres) et de doubles courbes de Gauss. La surface moyenne des feuilles était d'environ 5 cm^2 (distribution log-normale dans une gamme de 2 à 12 cm^2). En considérant la totalité des couronnes des arbres, la densité moyenne des feuilles était d'environ 2,6 m^2m^3 ; le maximum de surface foliaire se situait dans les strates entre 1,5 et 3m, et diminuait rapidement vers la base de la couronne et plus graduellement vers le sommet de l'arbre. Le volume foliaire des couronnes des oliviers (en moyenne 33,2 m^3) contenait en moyenne 145 000 feuilles pour un total de 72,6 m^2. L'indice foliaire à l'échelle de l'oliveraie ($LAI_{oliveraie}$ = 0,96), était plutôt peu élevé, du fait du faible nombre d'arbre à l'hectare. Cependant, lorsque l'on prenait en compte uniquement la projection des surfaces des couronnes (en évitant les espaces libres entre les arbres) le *LAI* moyen atteignait environ 3,5 (écart de 1 à 7). Le modèle radial de distribution des feuilles dérivé de l'analyse d'image révélait un pic de LAI_{rad}à une distance d'environ 60 à 70 % du rayon des couronnes des arbres. L'utilité de ces différentes approches pour l'estimation de paramètres allométriques est discutée.

photographie des contours / analyse d'image / modèle géométrique / distribution verticale et radiale des feuilles / dommages au tronc / forme de la couronne / biométrie

1. INTRODUCTION

Methods for the rapid estimation of leaf area and of leaf area distribution within mature trees are required for many studies that aim to up-scale physiological measurements to the canopy or regional scale. The present study was performed within the EU project WATERUSE, which focused on evaluation of alternative techniques for determination of water budget components in water-limited, heterogeneous land-use systems in the Mediterranean region. This paper concentrates on leaf area estimation from old olive trees at one experimental site in Italy, and relates especially to the scaling up of leaf and

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plant-scale measurements to the orchard. The leaf area analysis provided one component of a complex study involving detailed micrometeorological (e.g. eddy covariance [20,27]), soil geophysical [1,8,13] and physiological (e.g. stomatal conductance and sap-flow [6,9,18]) measurements relating to transpiration and water use from the orchard.

In spite of the long-term cultivation of olive trees in Mediterranean countries, little is known about the leaf distribution in old solitary growing trees in orchards. Most recent literature has been focused on verification of different methods to estimate leaf area in young trees, much smaller than those in our study. For example the leaf area index (*LAI*) has been estimated from the transmittance of radiation at various angles, when a plant canopy analyzer LI-COR LAI-2000 was tested in Spain [26]. Good results were also obtained when applying hemispherical photography in a young olive orchard in Italy [12] or even in somewhat older orchards in Tunisia [7]. The difficulty of applying these techniques to older trees arises because of the greater heterogeneity of canopy structure and of leaf distribution in older trees.

This study focused on the description of stand biometry and leaf distribution for the first time in an old olive grove, it also provided and evaluated a range of new technologies for obtaining such information that could be much more widely applicable to various tree crops. We consider separately vertical leaf distribution, which is particularly important for many purposes from productivity estimation to physiological studies including gas exchange and crop water balance [9,18], and radial leaf distribution, which is particularly relevant for interpretation of remotely sensing images [2]. Leaf and crown parameters evaluated from the side (i.e. frontal) are important for studies evaluating the aerodynamic resistance of the stand [20,27].

2. MATERIAL AND METHODS

2.1. Experimental site

The experimental plantation of olive (*Olea europea* L., cv. Coratina) was located at the farm "Torre di Bocca", near Andria, on the "Murge" upland of Puglia region, in southern Italy (41° 13' N, 16° 09' E, altitude 170 m). In Puglia, olive groves extend over 360 000 ha (approximately 40% of the area of olive cultivation in southern Italy) [29]. The area is characterised as semi-arid, with average annual rainfall of 530 mm, distributed from September to April; yearly averages of minimum and maximum temperatures are 11 and 21 °C, respectively. The 0–0.2 m topsoil layer is a loam (USDA texture class), showing remarkable spatial variability in particle size distribution. Calcareous materials are found in the topsoil, and at different degrees of weathering throughout the soil profile. Plants (approximately 80 years old) were trained with the vase system and the orchard was drip-irrigated. A 9 100 m^2 area consisting of 12 rows and 10 columns was chosen for detailed analysis.

2.2. Measurement of stand biometry

Trunk circumference was measured at the height of 1 m in all trees at the experimental site (trees were usually branching above this height, so they could not be measured at the forest standard height of 1.3 m). Total stem circumference (C_{total}) and the living part of it (C_{live}) were distinguished, because there were many lesions in stems, where wood was missing (e.g. some stem segments were severed by a chain saw) or rotten. Crown radii (r_c) of all 120 trees at the plot were measured from four cardinal points (eight in large trees) and crown projections (A_{c_proj}) were calculated as circles from mean crown radii (r_{c_mean}). The heights of tree top and crown base were measured using a calibrated stick with a scale-step of 0.1 m. Biometric parameters were calculated for each sub-plot and for the entire stand (expressed per ha).

2.3. Measurements and a model used for calculation of leaf distribution

Leaf area distribution was estimated using a combination of three approaches: (1) a simple composite geometrical canopy-layer model, (2) ground-based side images evaluated by the image analysis software and (3) rain-water holding capacity of foliage (when considering radial pattern of leaf distribution only).

The geometric canopy-layer mode, took into account the total volume occupied by crowns, the empty space within this volume (due to regularly severed branches in mid crown by pruning) and the volume actually occupied by foliage (Fig. 1). The actually foliated volume of hollow crown (V_{hol}) was expressed as $V_{hol} = V_{cyl} - V_{con} - V_{cor}$, where the cylinder volume (V_{cyl}), represents the crown projected area and a crown height calculated as the difference between heights of crown top and crown base; V_{con} is the volume of an inverted cone (whose dimensions were the diameter of the projected crown area and the crown height) representing the unbranched area at the center of the tree canopy; and V_{cor} which is a further correction to simulate the regularly removed branches along the watering pipeline, equaling 1/4 of the calculated volume (1/8 at each side of crown).

Mean leaf area density (m^2 m^{-3}) was measured on a series of about 700 shoots growing on about a hundred typical small and large branches distributed over the canopy in two sample trees and used to verify the model and to test the validity of equations used to convert foliated volume to leaf area. Leaves were counted on each numbered shoot and their area was estimated on a series of sub-samples (mean of 30 leaves each). There were 40 692 leaves on sampled branches in the large sampled tree (No. 44), which were assessed by leafed volume to represent about 15% (1/6) of the whole tree crown (mean of 5 independent assessments) and gave a mean leaf area density of 2.87 m^2 m^{-3}. Branches on the small sample tree carried 13 080 leaves, and gave a mean of 2.25 m^2 m^{-3} (thus the overall mean was 2.56 ± 0.31 m^2 m^{-3}, i.e. ±12%). Actual leaf area (A_{leaf}) was derived from rectangular area of leaf blade (A_{rect}), calculated from its length (L_{leaf}) and width (W_{leaf}); true A_{leaf} was obtained when leaf area was measured in 5 mm long sections (resulting in: $A_{leaf} = A_{rect} \times 0.687$; $r^2 = 0.982$). Xylem cross-sectional area was determined in all studied shoots and branches after subtracting bark from the total cross-sectional area.

The vertical distribution of leaf area was calculated for layers of the canopy 0.5 m deep using a similar approach as in our preceding studies [3–5, 16, 17, 23]. Leaf amounts in 0.5 m deep canopy layers were splained by an equation, which parameters were generalized according to available stand biometry data. Having in mind the irregular and changing form of crowns, a double Gaussian curve was applied, where y = leaf area per 0.5 m deep canopy layer and x = height. The parameters have clear physical meaning (a, d = amplitude;

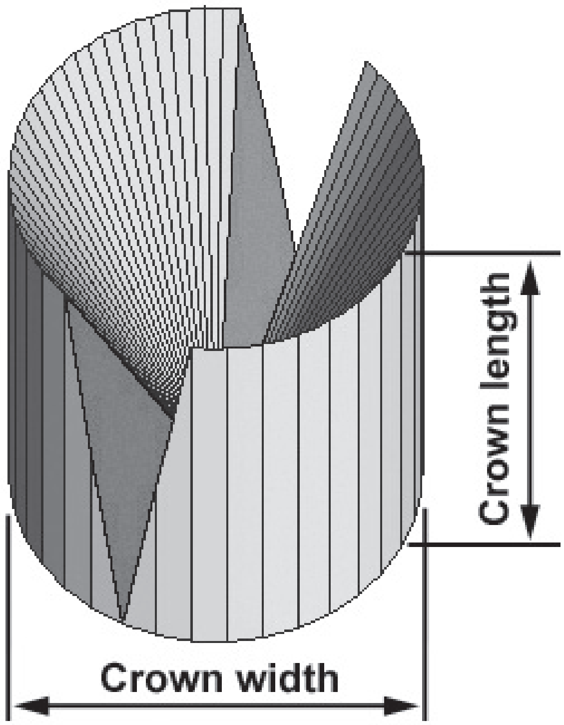

Figure 1. Scheme of the geometrical model of an olive tree crown composed of the cylinder volume, from which the volume of overturned cone (opened by regular pruning) and volume of the core (opened for watering pipeline) is subtracted. Mean crown width = 4.8 m, crown length = 4.1 m, starting at 0.8 m above ground, distance between neighbor crown edges = 3.9 m.

b, e = width; c, f = peak position, g = reduced tailing) and can be easily estimated, especially if relative height values are used

$$y = \{a \times \exp[-b(x-c)^2]\} + \{d \times \exp[-e(x-f)^2]\} - g. \quad (1)$$

Parameters of this equation were related to total stem circumference (C_{total} as the independent variable) and corresponding partial equations were calculated. Parameters of the main equation (Eq. (1)) for each tree size were derived using such equations, thus leaf area was derived for each layer (i) of each of (n = 120) trees in the stand. Total leaf area for each individual tree was obtained when summing values for all individual layers (m). Similarly total leaf area for the entire stand was calculated when summing total values of (n) individual trees.

The validity of the model was tested on a series of 700 shoots and branches from known positions on different trees, where leaf densities were measured manually. We considered regressions between actually measured values of leaf area in altogether 25 canopy layers and those calculated from the model.

2.4. The image analysis method

Entire crowns of 26 trees were photographed from different sides; selected crowns whose images did not overlap with other crowns behind them were digitized and the images were analyzed in terms of foliage density using an image-analyzer. The branches for which leaf density was measured directly were used for calibration of entire crown images. Images of whole tree crowns and separately of measured branches were prepared by deleting some interfering parts of images (skeleton of branches) and adjusting contrast and brightness, if necessary (Figs. 2 and 3). Then the images were converted to a binary form and we counted numbers of black and white pixels by the special software (Image Tool, version 3.0, The University of Texas Health Science Center in San Antonio, internet-available (http://ddsdx.uthscsa.edu/dig/itdesc.html). Full black objects (branches) and large white areas of the image were hand marked; their area in pixels was counted and subtracted. In this way the final ratio of black and white pixels was estimated and the black area same way as in the model in 0.5 m layers and used to estimate the general pattern of vertical leaf distribution.

Radial leaf distribution was derived approximately from the same images as used for the vertical distribution, taking account of true crown geometry. The side view used showed only the cumulated foliage across the whole crown at a certain point; the sum of all tangential sections i gave the total (Fig. 4). In order to derive the radial distribution, we assumed that leaf density was homogeneous over the whole foliated crown volume. Then we divided the amount of foliage in the tangential image of a particular section L_{tg_i} by the volume of corresponding crown part, the sphere layer V_i, where h is layer thickness and r_1 and r_2 are smaller and larger radii of the layer. We obtained the leaf area in a particular unit volume this way (this differs from the "homogenous" mean density because of different depths of the canopy along the tangential view). Finally we multiplied the particular unit volume (with corresponding leaf area) by the height of the canopy above the corresponding section of the radius.

In addition, some images were taken of individual trees from above from two micrometeorological towers installed in the orchard using usual digital camera and Infrared Solutions Snapshot 525 camera [2].

In addition, radial leaf distribution was also assessed indirectly from measurements of the rainwater holding capacity of foliage in one experimental tree. This was calculated on the basis of measured throughfall at the ground level at eight points across crown diameter and expressed as a percentage of precipitation in the open (outside crown). Water-holding capacity of branches with known leaf area (the difference in weight between wet and dry branch) was measured gravimetrically.

3. RESULTS

3.1. Stand biometry

The stocking density of the olive grove was 132 trees ha^{-1}, mean spacing 8.7 m and mean social area (proportional to spacing and tree size) was about 76 m^2 per tree. More details are given in Table I. Distribution of stocking density and stem circumference according to classes are shown in Figure 5A. Heavy pruning, together with the very irregular stem shapes, explain why the relationship of projected crown area to stem circumference (both total and living) was poor, with r^2 around 0.06. The range of top heights was rather narrow (3.8 to 5.5 m), with a mean of 4.9 m. The top height was regularly related to total stem circumference (Fig. 5B), while the height of crown base was very similar in all trees (about 0.8 m), probably as a result of grazing, with only some thin branches of

A

B

Figure 2. Olive tree crown image against free sky (A), and when converted to a binary form (B) (compare to Fig. 3 with slightly different density).

A

B

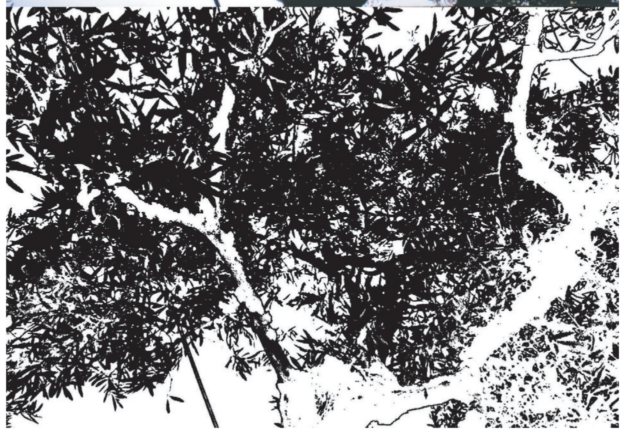

Figure 3. Olive tree branch image against free sky (A), and when converted to a binary form (B) (compare to Fig. 2 with slightly different density).

the largest trees hanging down almost to the ground (see also Fig. 2A). The dead part of the tree circumference averaged 40% of healthy living tissue in larger trees and ranged from about 30% in small (usually young) trees (C_{live} = 30 to 50 cm) to about 60% in slightly larger trees (C_{live} = 50 to 70 cm) (Fig. 6A). The highest damage to tree stems appeared when they reached the circumference of about 70 cm, after this it remained relatively stable (Fig. 6B).

The horizontally projected crowns of trees (for the mean tree $A_{proj} = 17.7\ m^2$) varied only little with view direction. Mean crown radius was 2.4 m, radii at directions to NE, SE, SW and NW were of 2.39, 2.48, 2.23 and 2.33 m, respectively. Projected frontal area of olive crowns from the side reached for the mean tree $A_{front} = 18.5\ m^2$, when considering tree spacing (= 8.7 m) and mean height (= 4.9 m), it gave the mean "front leaf area index", LAI_{front}, amounting 2.3.

3.2. Individual leaves, branches and allometric relationships

Using the leaves whose areas were measured for calibration purposes, individual leaves varied in size from about 2 cm^2 to about 11 cm^2, with a mean leaf area of 4.9 cm^2 (Fig. 7A). This value differed slightly in individual sub-samples taken from branches growing in different parts of the crown, but no clear pattern was found, largely because of the irregular presence of very small leaves on the young shoots. Leaf length (y_1) had a higher impact on leaf area (x) in small leaves and less in large ($y_1 = 3 + 5.1 \times [1 - \exp(x/2)]^{5.5}$), while the impact of leaf width (y_2) was similar in all leaf sizes ($y_2 = 0.504 + 0.13 \times x$). The relationship between leaf area (A_{leaf} in m^2) and xylem cross-section area (A_{xyl} in cm^2) which was derived from the data for the 700 shoots and branches showed that: A_{leaf} =

Table I. Main biometric parameters of the olive (*Olea europea* L.) grove. Values of the mean tree and stand area unit (1 ha) with stocking density of 132 trees ha^{-1} with corresponding standard deviation for appropriate variables are given.

Biometric parameter	Mean tree (Units)	Stand total (Units)
Stem circumference at 1 m – total	110.2 ± 3.3 (cm)	14 500 (m ha^{-1})
Stem circumference at 1 m – live	80.8 ± 2.2 (cm)	10 700 (m ha^{-1})
Height (total length)	4.94 ± 0.06 (m)	650 (m ha^{-1})
Projected crown area	17.7 ± 0.42 (m^2)	2 330 (m^2 ha^{-1})
Leaf area (leaf blade area)	72.6 ± 1.95 (m^2)	9 590 (m^2 ha^{-1})
Foliated crown volume	33.2 ± 0.89 (m^3)	4 380 (m^3 ha^{-1}]
Leaf number	145 300 ± 3 890 (leaves)	19.2×10^6 (leaves ha^{-1})
Leaf density in fully foliated volume		2.54 (m^2 m^{-3})
Leaf density in mean foliated volume		2.16 (m^2 m^{-3})
Leaf density per projected crown area		4.1 (m^2 m^{-2})
Leaf density per unit of stem circumference (total)		0.66 (m^2 cm^{-1})
Leaf density per unit of stem circumference (live)		0.90 (m^2 cm^{-1})
Leaf density per projected crown area		8 230 (leaves m^{-2})

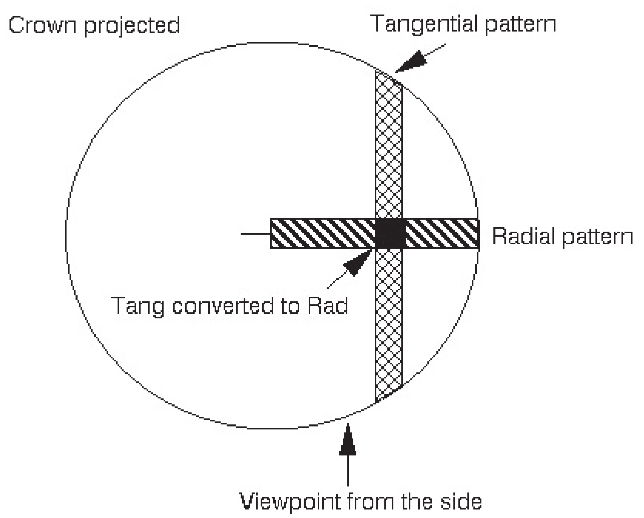

Figure 4. Scheme applied for calculation of radial pattern of leaf distribution in olive trees from images characterizing vertical and tangential distribution. The amount of foliage in the tangential pattern of a particular section (L_{tg_i}) was divided by the volume of corresponding crown part, the sphere layer (V_i=1/6 πh ($3r_1^2$+$3r_2^2$ + h^2), where h (= 0.5m) is layer thickness and r_1 and r_2 are smaller and larger radii of the layer).

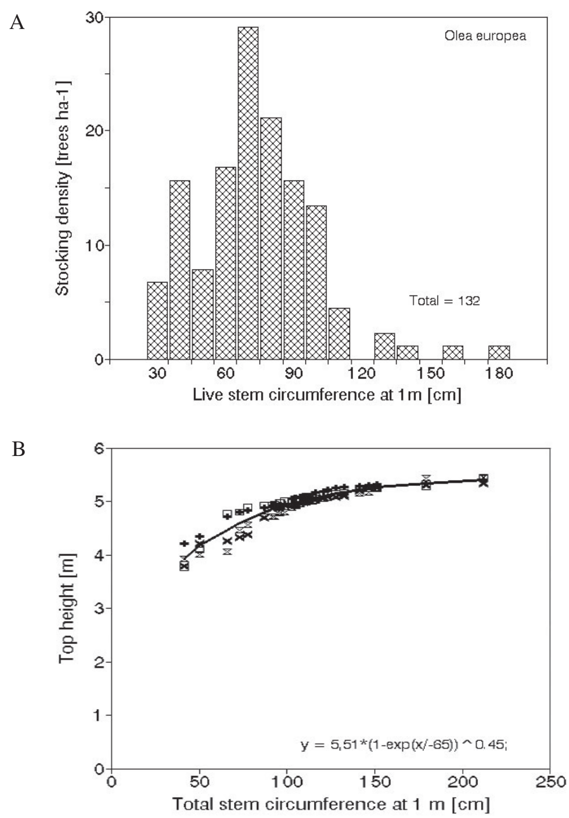

Figure 5. Tree size distribution (A) and relationship between height and trunk circumference (B) in an olive grove in Andria 2002.

$0.33 \times A_{xyl}^{0.795} - 0.0029$; $r^2 = 0.963$, $SE = 0.148$ (Fig. 7B). (Bark thickness B_t in mm can be derived from branch diameter in mm D_b as: $B_t = 0.7 + \{3.7 \times [1 - \exp(D_b/-46)]^2\}$.) Allometric relationships were good for the whole range of measured branch diameters (from above 2 to over 100 mm). The greatest variation occurred in small shoots (because some were vigorous and some declining), but relationships calculated separately for different ranges of diameters did not improve the fit.

3.3. Leaf distribution on the level of individual trees

A calibration ratio of black and white pixels to the mean leaf density of measured branches gave a value of

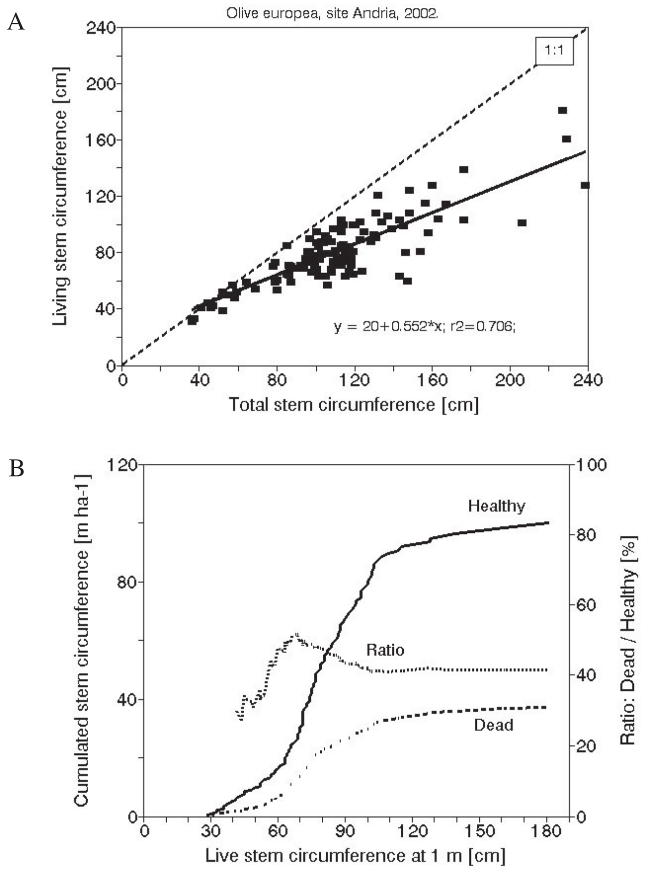

Figure 6. Living stem circumference as a fraction of the total (A) and cumulated stem circumference in healthy and dead trees of different size and their ratio (B).

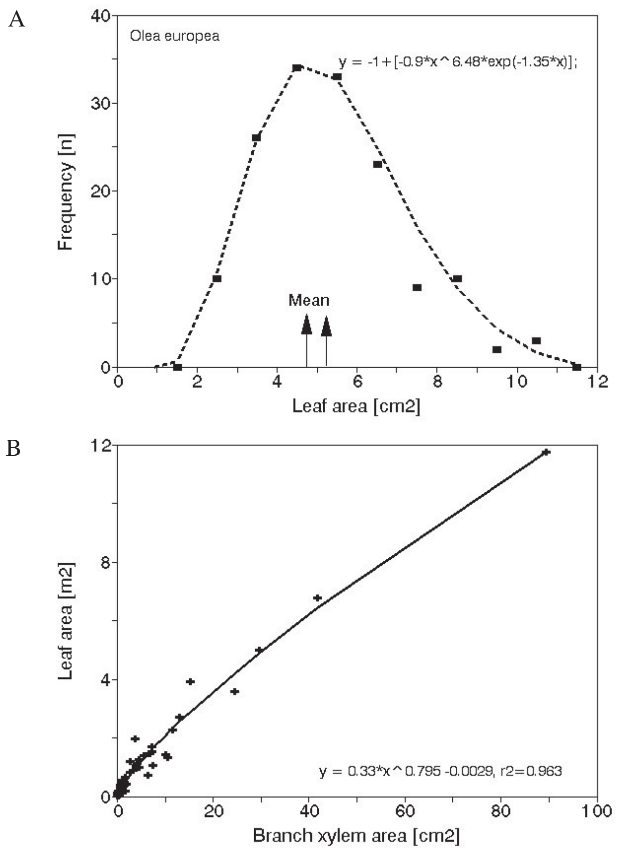

Figure 7. Individual leaf area distribution in olive trees (A), arrows show the range of mean values calculated for different trees) and allometric relationships between xylem cross-sectional area and leaf area measured in altogether 700 olive shoots and branches (B).

approximately 0.25 per 1 m^2 m^{-3} (Tab. II), which approached the value calculated for the crown of the mean tree (0.33 – this value is higher due to thicker layer of included foliage than in single branches). The model describing vertical leaf distribution at the whole tree level was characterized as follows: some generalizing coefficients (a, h, g) of the main equation used in the olive grove were linearly related to the total stem circumference, others (b, c, e, f) were found to be exponentially related to stem circumference (Tab. III). The resulting vertical leaf distribution differed substantially in amplitude between individual trees, but also slightly in its form. Maximum leaf area occurred in canopy layers between 1.5 to 3 m (Fig. 8) and it ranged between about 4 to 13 m^2 per 0.5 m^{-1} of canopy depth in trees of different size. Leaf area density estimated by the image analysis of olive crowns and density derived from the geometrical model showed rather good agreement ($r^2 = 0.964$) when applied to the calculated pattern of vertical distribution – values of measured and calculated leaf area in canopy layers (Fig. 9). The total leaf area per tree (y) was dependent on total stem circumference of individual trees (x) in an exponential way within a given range of tree size ($y = 40.5 + x^{0.35} - 136$). It ranged within one order (between 20 and 220 m^2 per tree) in the given stand. Variation occurring in leaf area density per layer along tree height was about 5% and total leaf area in trees of the same circumference about 10%. There was high variation of LAI between individual trees, which ranged from 1 to 7.

The radial pattern of leaf distribution could not be estimated with reasonable accuracy from the geometrical model, however it was made accessible through the image analysis approach. Radial pattern of leaf distribution derived from image analysis indicated peak LAI_{rad} values at a distance from the stem of about 60 to 70% of crown radius in trees of different size and total LAI values. Actual LAI_{rad} data were probably estimated with larger error then usual (vertical) LAI data due to the more complex calculation. However, it is clear that peak values occurring near the crown edge were several times higher then values occurring near main stems, i.e., close to crown center (Fig. 10A).

A similar radial pattern of leaf distribution was also apparent from the foliage water holding capacity data, obtained when the rainfall was large enough to saturate the olive canopy (in this case relative interception may reach up to 25% at about 5 LAI [10,11]. In this case the radial pattern of leaf distribution

Table II. Example of image analysis of canopy demonstrated for three entire tree crowns and six individual large branches.

	Entire crowns				Individual branches	
	Black (%)	White (%)			Black (%)	White (%)
Tree 1	74.73	25.27	Tree A (small)	Branch 1	63.91	36.09
Tree 2	60.84	39.16		Branch	2 67.98	32.02
Tree 3	65.25	34.75		Mean small	65.95	34.06
Mean tree	66.94	33.06		Standard error	1.66	1.66
Standard error	2.51	2.51	Tree B (large)	Branch	1 70.18	29.82
				Branch	2 75.12	24.88
				Branch	3 64.46	35.54
				Branch	4 67.98	32.02
				Mean large	69.92	30.08
				Standard error	3.86	3.86

Table III. Additional equations and their parameters used for deriving values of coefficients of the main, double Gaussian equation ($y = \{a\exp[-b(x_1 - c)^2]\} + \{d\exp[-e(x_1 - f)^2]\} - g$; x_1= height in m) applied for vertical leaf are distribution in olive (*Olea europea* L.) trees in 0.5 m deep canopy layers (y in m^2 0.5 m^{-1}).

Coef. of the main equation		Form of additional equations (x_2= total stem circumference in cm)	Coefficients of additional equations p	q	s
a	(amplitude1)	a = px_2;	0.0592	–	–
b	(width 1)	b = $p + q\exp(sx_2)$;	0.348	0.05	–0.011
c	(position 1)	c = $p + q\exp(sx_2)$;	3.25	–0.85	0.005
d	(amplitude 2)	d = px;	0.1134	–	–
e	(width 2)	e = $p + q\exp(sx_2)$;	0.30	10.0	–0.053
f	(position 2)	f = $p + q\exp(sx_2)$;	5.29	–4.2	–0.004
g	(tailing)	g = $p + qx_2$;	0.02	0.031	–

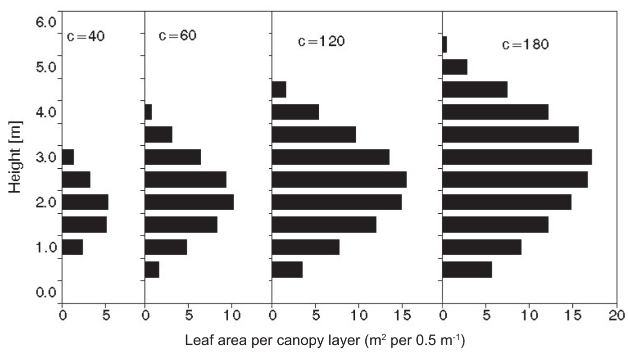

Figure 8. Vertical distribution of leaf area (in 0.5 m deep layers) in individual olive trees (examples of trees with different stem circumference, c, at 1 m).

showed a single peak with maximum (LAI^*_{rad} = 1.4) at about 80% of crown radius and minimum (LAI^*_{rad} = 0.6) at the crown center (Fig. 10B). Values of LAI^*_{rad} estimated this way (when input data were also modified by tree skeleton) can be only relatively related to true LAI_{rad} estimated by other measurements. The situation with LAI_{rad} becomes even clearer when it is expressed over the whole crown projected area. We should have in mind that under crown contours visible in true colors (Fig. 11A), or infra-red (false) colors (Fig. 11B), are very different values of LAI_{rad} (Fig. 11C). Images of a particular tree and of a scheme given by the model are certainly not identical, but they all illustrate the situation.

3.4. Leaf distribution at the stand level

At the stand level, maximum leaf area within one 0.5 m layer reached 1 600 m^2 per ha or about 0.17 LAI (Fig. 12). The total stand LAI was about 0.96 when expressed per total orchard area. The same value of LAI was obtained when integrating "horizontally" individual trees or when integrating all canopy layers in vertical direction or cumulating values from all individual trees. However, when expressed for the projected crown areas, the mean LAI reached about 3.5.

4. DISCUSSION

4.1. Stand biometry

The stocking density of the studied olive grove was rather sparse, but typical of the region for orchards originally planted

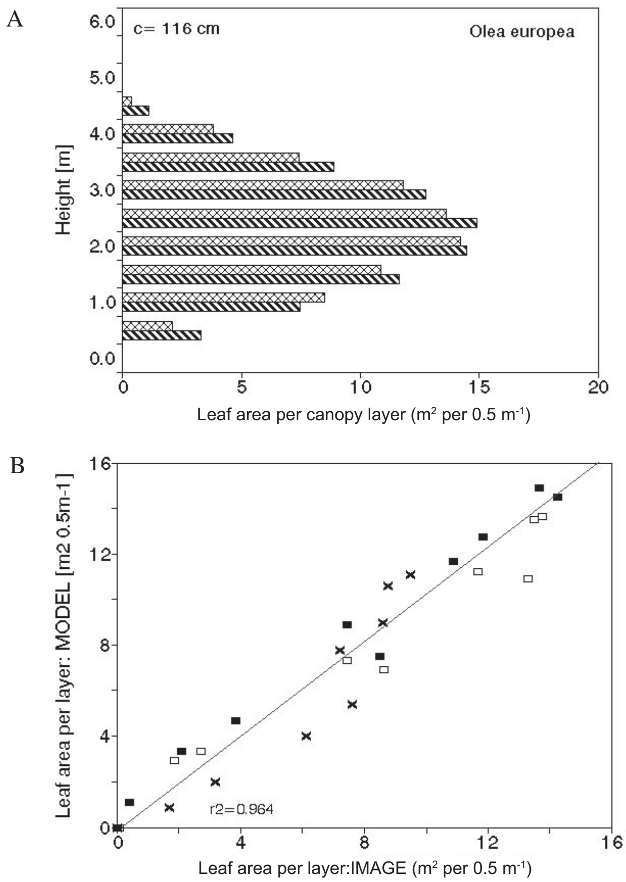

Figure 9. Leaf area per 0.5 m deep canopy layer in olive trees estimated by the geometrical model and by the image analysis technique. An example of vertical profile (A), where crossed columns represent data from the image and dashed data from the model and the regression (B), where full squares, empty squares and x-marks are for three trees with circumference of 116, 104 and 80 cm, respectively.

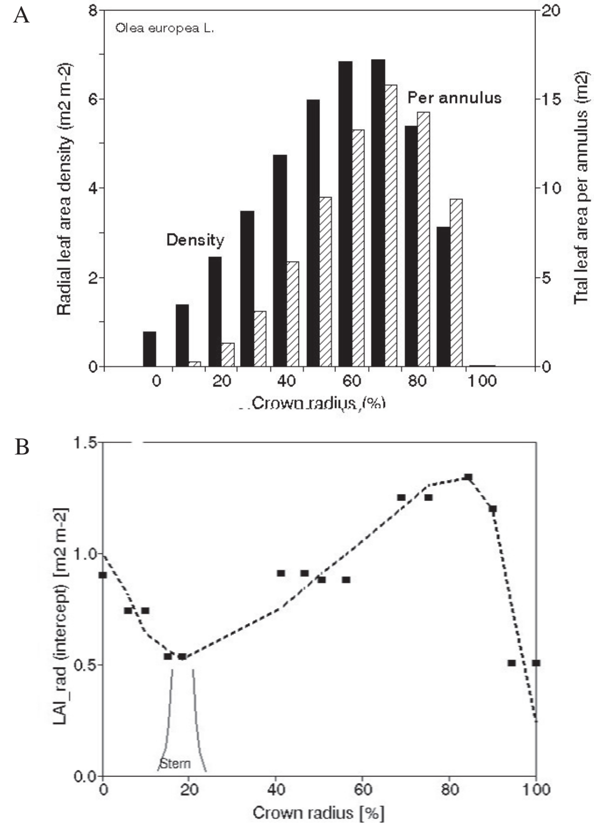

Figure 10. Radial pattern of leaf area density (LAD_{rad}) and total leaf area per annuli distribution in olive crowns, when estimated using image analysis (A) and indirectly derived from water holding capacity of foliage (B).

to grow without irrigation. Newly applied drip irrigation would now allow a higher stand density [15,28]. The variation in biometric parameters between trees was large for several reasons including: (1) age differences (some young trees were replaced), (2) pruning treatment (major branches have been removed from crown centers to improve canopy illumination and from two directions at crown edges to make free space for pipe lines) and (3) tree health (there were several rotten or severed branches with consequent variation in total and live stem circumference). The percentage of lesions increased with age after the first pruning at stem circumferences around 70 cm.

4.2. Variation in individual leaves and branches

Individual leaves showed the usual size distribution. Leaves typically grow first in length and only after reaching an area of about half of their maximum size (i.e., around 5 cm^2) they continued growing in length and width in a similar rate. The allometric relationship between A_{xyl} of branches and their A_{leaf} explained over 96% of the variation and appeared adequate for further application in related physiological studies (e.g. calculation of leaf area for branches of known diameter, where sap flow was measured).

4.3. Geometrical model and image analysis

Spatial and vertical leaf area index in deciduous trees have been analyzed many times previously using plan canopy analyzers or destructive sampling (e.g., [5–7,12,16,17,22,23,26]). Our geometrical model simplifies crown shapes and supposes homogenous leaf distribution within the foliated canopy volume; there seems little advantage in a more complex model because of the tree variability. Estimation of leaf distribution based on side-image analysis is dependent on positions of individual leaves in relation to the camera, where leaf angles play an important role. Leaf angles in olive are known to vary with water stress [19] with the most frequent (1/3 of the total) angle at about 60 ± 35° from the horizontal plane under drought and at 50 ± 35° under wet conditions. Leaf angle also changes along the shoot axis with young leaves growing with

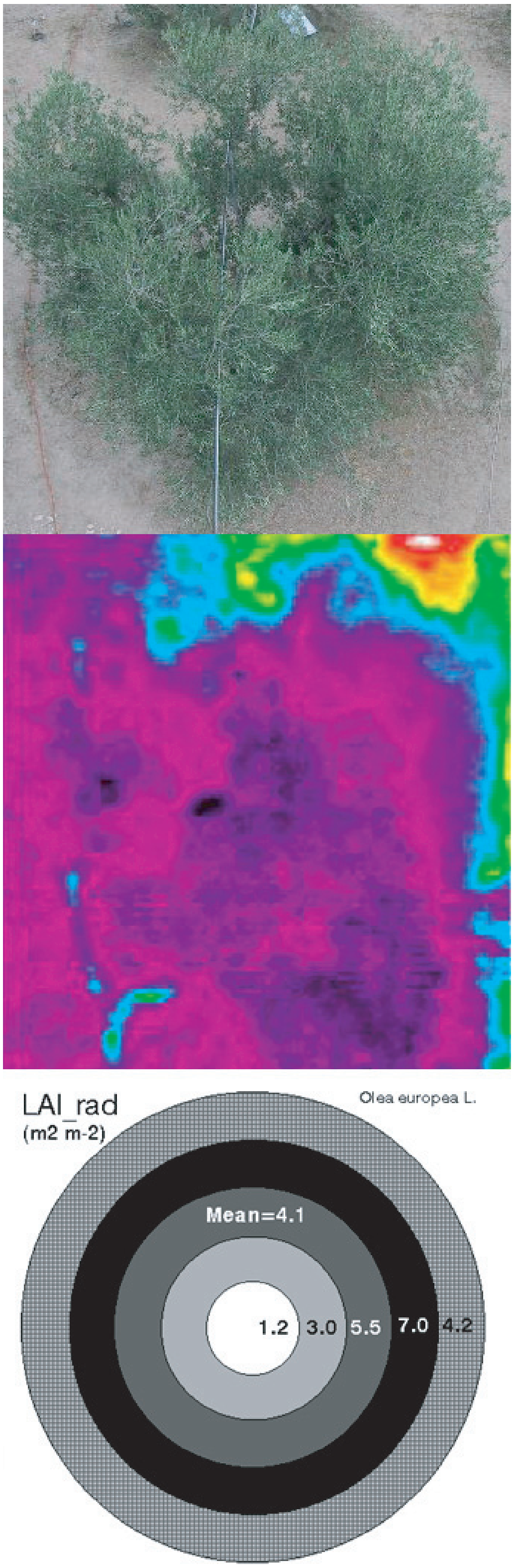

Figure 11. Remote images of an olive crown (taken from the tower) in normal (A) infra-red (false) colors (B) and radial leaf area index (LAI_{rad}) distribution (C) calculated across mean olive tree crown (diameter 2.4 m). The scale corresponds to that shown in Figure 9A.

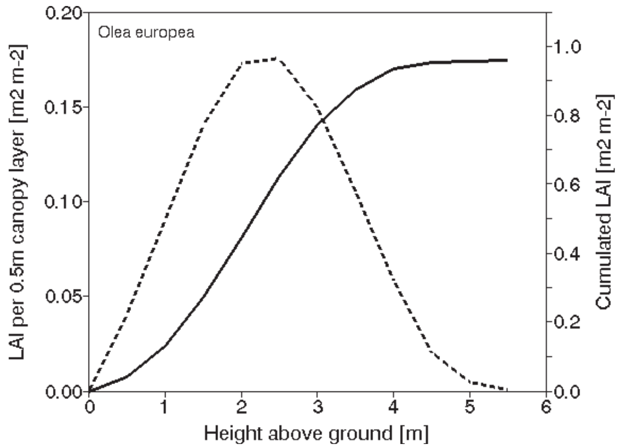

Figure 12. Vertical leaf area index (LAI) distribution in the olive grove (entire stand level) and its cumulative when taking into account 0.5 m deep canopy layers.

minimum deviation in direction of the shoot axis, and the angle increasing to about 25° at the level of the 10th leaf [21] with some effect of drought. The effective leaf blade width may also change due to rolling, but these effects were not included in the present model. Values of the image-estimated leaf area were a bit lower, probably because of varying leaf orientations and overlap. However, the very good agreement of two independent approaches for determining olive leaf distribution ($r^2 = 0.96$) does indicate good applicability of the results for further use.

4.4. Leaf distribution on the level of individual trees

Gucci et al. [12] estimated plant area index (PAI, including leaf and skeleton indexes) by conventional gap fraction analysis of hemispherical photography and reported values of 34 and 63% of that determined destructively in 1-year-old plants and young mature trees, respectively. This ratio is close to that of black and white mean images of leaf density of our mean olive tree, which reached 33% per 1 m^2m^{-3}. Tombesi et al. [24] studied rather small olive trees with a canopy volume of 20–22 m^3 (about half that of our old trees). The leaf area index (per unit projected tree area) was rather high for individual trees reaching an LAI_{ind} about 4.1, and was close to that in lightly – or rarely – pruned trees (LAI = 5 to 6; [24]).

The estimated radial distribution of foliage within the canopy (from image analysis) showed a significant concentration close to the outer edge of crown, where its density was several times greater than in mid crown as a result of long-term systematic pruning. This trend was confirmed both by actual measurement and by the rainfall interception data, though the latter only studied one tree with a rather well developed crown. Similar approaches have been tried previously [10, 11, 25]. LAI_{rad} expressed over the entire crown projected area indicates the importance of this parameter for more detailed interpretation of remote sensing data and also for studies of interception or soil water supply from precipitation. Such information may be also important for root studies, because tree roots in non-irrigated orchards will probably avoid that part of the rooting zone with minimum throughfall. Though we are not aware of any data for old olive trees for comparison. Published results in natural closed stands e.g. of laurel trees show an opposite trend in LAI_{rad} [17], which underlines the impact of crown pruning in orchards.

4.5. Leaf distribution at the stand level

Villalobos et al. [26] found that PAI estimates were close to LAI in olive orchards, as the fraction of total area corresponding to leaves was > 90% in olive trees grown in the field. PAI reached about 4 in young experimental olive stands of high stocking density (0.5 to 2 trees per m^2) [14]. Foliated volume of olive crowns and corresponding leaf area index on the stand level ($LAI_{grove} = 0.96$) were rather low due to low stocking density, similar average value estimated in the olive grove near Cordoba in Spain was little higher ($LAI_{grove} = 1.1$) [10, 11]. It is interesting to compare such LAI values with partitioning of leaf dry matter which was assessed in leaves of young olives to about 37% of their total biomass, while about 26% was partitioned to roots [14].

5. CONCLUSIONS

Leaf distribution in solitary growing trees (e.g. in sparse plantations or orchards) can be alternatively estimated on the basis of geometrical models (using basic biometric parameters of stems and crowns) as well as on the basis of side photographic images and from leaf water holding capacity.

Both vertical and radial leaf distribution (as well as vertical, radial and frontal LAI) can be derived from similar field measurements and scaled up from individual trees to entire stands (orchards) using stand inventory data on trunk sizes. Vertical distribution can be related to leaf illumination, radial distribution can help with interpretation of remote sensing images, interception of water and eventually root distribution, frontal distribution is a background for aerodynamic resistance calculations.

Leaf distribution in olive trees is generally similar to other broadleaved tree species, but the variability between individual trees in orchards is likely to reflect pruning regime and will lead to a need for derivation of allometric parameters specifically for each situation.

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