

## LAI estimation of natural pine forest using a non-standard sampling technique

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### Abstract

Indirect methods to estimate the leaf area index (LAI) in forests have been less successful than the more costly direct (allometric) methods. Our aim was to find an indirect method to estimate LAI efficiently, using the LAI-2000, Plant Canopy Analyzer, in forest stands of *Pinus halepensis*. The direct LAI estimate of individual trees was carried out through destructive sampling. In forest stands, direct estimates were derived from the allometric relationship between leaf area per tree and diameter at breast height (DBH). Indirect estimates were conducted with a standard strategy (i.e., multiple readings per plot placing the sensor at sites selected systematically on a transect) and with our non-standard strategy consisting of reading at a single point per plot, standardising the distance and orientation from a subject tree to reduce variability. The non-standard sampling strategy was a procedure as effective and accurate as the indirect standard strategy (transects), but more labour-efficient. The indirect estimate of the LAI-STAND using the LAI-2000, with either strategy was unbiased. These results advocate the use of a non-standard strategy scattering the sampling points throughout the stand rather than concentrating all the effort on a few plots following a standard strategy and leaving the rest of the stand unchecked. Also, both the standard and the non-standard strategy yielded significant regression models to estimate forest stand parameters, which are labour expensive to measure using direct methods. Thus, the LAI-2000 could be used as a tool to estimate such parameters indirectly. ©2000 Elsevier Science B.V. All rights reserved.

**Keywords:** Leaf area index; Leaf area; LAI-2000; *Pinus halepensis*; Allometric relationships; Sampling strategy

### 1. Introduction

Canopy structure has great importance in studies of the interaction between plants and their environment. This term is defined as the amount and organization of plant material above ground (Norman and Campbell, 1989) or, additionally, as the group of traits describ-

ing the shape, size and geometry of a plant or plant community (Ross, 1981). In practice descriptions of canopy structure are based on a few parameters. The foliage surface per ground area (Leaf Area Index, LAI) is the parameter most often used, since it has been shown to be associated with key ecosystem processes.

There are several procedures to estimate LAI, both direct (Daughtry, 1990) as well as indirect (Welles, 1990; Welles and Cohen, 1996; see reviews of both methods in Ross, 1981, and Norman and Campbell, 1989). Because direct methods are slow and labor

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intensive, indirect methods are being increasingly used. Several instruments (see Welles, 1990; Welles and Cohen, 1996) estimate LAI indirectly by measuring light transmission and using Beer-Lambert's law (Monsi and Saeki, 1953; Anderson, 1971) or gap fraction theory (Lang and Yueqin, 1986; Perry et al., 1988). One of these instruments is the LAI-2000, Plant Canopy Analyzer (Li-Cor, 1991a), which measures diffuse radiation in five distinct angular bands or rings (7, 23, 38, 53 and 68°) around the zenith simultaneously.

The LAI-2000 has been used with reasonable success to estimate LAI in continuous and homogeneous canopies, such as agricultural crops and grassland (see references in Welles and Cohen, 1996). In discontinuous and heterogeneous canopies, the efficiency of the LAI-2000 has not yet been fully established, probably as a result of the poor agreement between direct and indirect estimates, particularly in natural unmanaged pine stands (Sampson and Allen, 1995) or because regression models have non-zero intercepts and slopes different from unity.

Research has been published on LAI from forest stands with virtually continuous canopies (few wide gaps), including artificial monospecific (Gower and Norman, 1991; Deblonde et al., 1994; Moser et al., 1995; Smolander and Stenberg, 1996), natural monospecific (Chen and Black, 1991; Sampson and Allen, 1995), and natural mixed stands (Vertessy et al., 1995; Strachan and McCaughey, 1996).

The studies on LAI estimates in forest stands, using either the LAI-2000 or other instruments, have been carried out with standard strategies consisting of recording multiple readings within each plot, at sites selected either at random (Gower and Norman, 1991; Vertessy et al., 1995; Eschenbach and Kappen, 1996), along transects (Deblonde et al., 1994; Vertessy et al., 1995; Strachan and McCaughey, 1996), in grids (Stenberg et al., 1994; Smolander and Stenberg, 1996), or by other criteria (Moser et al., 1995).

Very few studies have considered the effect exerted by the precise point where the LAI-2000 readings are taken on the indirect estimate of LAI in a forest stand. Such studies have been carried out in agricultural crops (e.g. in rice crops, Dobermann et al., 1995; in vineyard, Ollat et al., 1998) because these are linear crops with important and systematic gaps in the canopy. Similarly, important gaps often occur

in some natural mediterranean forest stands at low densities. If significant gaps are associated with dense foliage, the LAI-2000 readings will underestimate the direct LAI (Lang and Yueqin, 1986; Li-Cor, 1991a). As a consequence, in such conditions and despite using a strategy of multiple-readings per plot, the LAI-2000 will amplify the LAI-direct real variability (e.g. the sensor might sometimes be placed next to the stem, sometimes obscured by it — overestimating the LAI — and next measurement may be taken at a greater distance from a stem, either below a tree crown, or under an open area — underestimating the LAI). We believe the reason for this is that these methods do not standardise the sampling point with regard to the distance and orientation to the nearest tree.

It seems, thus, unlikely, that standard strategies can be effectively used in large heterogeneous forest stands. The reason is that these would require a large number of sampling plots according to inventory sampling theory, which involves a high cost in data collection. This standard methodology would only be possible in very homogeneous forest stands which require few plots to represent them.

Therefore, our aim was to propose a non-standard sampling strategy which reduced the variability in LAI-2000 readings by standardising sensor position with respect to the nearest tree, thus allowing a stand to be characterised with only a few scattered readings.

The need of a correction factor for LAI-2000 measurements, in conifer stands, has been suggested as a result of both foliage clumping and light interception by non-photosynthetic elements (Gower and Norman, 1991; Chen and Black, 1992a, b; Fassnacht et al., 1994; Chen, 1996). However, such coefficients may not be universally applicable (Deblonde et al., 1994; Sampson and Allen, 1995; Stenberg, 1996), and they are usually too costly to estimate, involving additional sampling procedures and requiring new instrumentation such as the Tracing Radiation and Architecture of Canopies (TRAC, Chen and Cihlar, 1995) or the Multiband Vegetation Imager (MVI, Kucharik et al., 1998) to estimate them. We believe that LAI-2000 and direct LAI estimates should be compared to examine whether the resulting regression models (obtained using an improved non-standard methodology), include implicitly such correction coefficients.

The objectives of our work were: (i) to develop a mathematical model to estimate the leaf area of individual trees, using allometric relationships; (ii) to obtain leaf area index values using direct estimates for individual trees, and allometric estimates in forest stands; (iii) examine how neighboring trees affect the leaf area and LAI of a subject tree; (iv) develop a new method to estimate indirectly the LAI of forest stands using the LAI-2000; (v) develop mathematical models based on LAI-2000 measurements to estimate forest stand parameters.

## 2. Methods

The study was carried out in a natural forest stand near the city of Albacete, Spain, during the months of January–May 1996 and April–May 1997. It was conducted on a 25 ha experimental plot placed 700 m above sea level (latitude 39°10'10"N, longitude 1°56'40"W), remarkably flat and with very small slope. The overstory was dominated by Aleppo pine trees (*Pinus halepensis* Mill.) and the understory consisted of a few individual Evergreen oak trees (*Quercus rotundifolia* L.), rising to a height of 2 m, with some bushes (height < 1.3 m) of the species: *Q. coccifera* L., *Q. rotundifolia* L., *Rosmarinus officinalis* L., *Thymus vulgaris* L., *Juniperus oxycedrus* L., *Rhamnus lycioides* L. and *Cistus clusii* Dun. The stocking density (mean ± SE,  $n=10$ ) of pines was  $812 \pm 87$  trees/ha. The stand consisted of two-cohorts (Oliver and Larson, 1996) as a consequence of selective felling carried out 15–20 years ago, which originated a DBH (diameter at breast height) distribution intermediate between an even and that of an uneven age stand. Basal area was  $16.8 \pm 1.0$  m<sup>2</sup>/ha, average height was  $7.09 \pm 0.29$  m and the crown coverage (computed as the sum of projected crown areas divided by plot area), was  $52.9 \pm 3.3\%$ .

The mean annual temperature is 13.6 °C and the average total annual precipitation is 353 mm. The phytoclimatic subtype is IV(VI)1(7): Mediterranean, fresh, semiarid of plateau (Allué, 1990). It should be noted that the 2 years preceding our study were warmer and drier than average (mean annual temperature 15.3 and 14.7 °C, respectively and total annual precipitation 273 and 271 mm, respectively), which might have influenced results as discussed further.

### 2.1. Direct estimate of the leaf area and LAI of individual tree

The LAI of an individual tree is defined as the ratio one half of the total leaf area (henceforth termed one-sided area) of all leaves (needles in our case) to the crown projected area (in m<sup>2</sup>/m<sup>2</sup>, DLLAI according to Welles, 1990; and Le Goff and Ottorini, 1996). In order to obtain direct estimates of leaf area and LAI in individual trees, 20 Aleppo pine trees were selected for destructive sampling (12 in February 1996 and eight in May 1997). The individuals were representative of the range of DBH in the stand (DBH range of 5–40 cm). The distance between the sampled trees was greater than 50 m.

A minor improvement in the direct estimation of leaf area was introduced in May 1997 to improve estimate precision as explained further.

#### 2.1.1. Direct estimate of the leaf area in February '96

DBH and crown projected surface ( $C_s$ ) were measured before each tree was felled. A rod with a plumb line was used to mark eight points which defined the crown boundary. A rod was placed in each point and then, polar co-ordinates of each point were referred to the stem. The area of the polygon thus defined (crown projected surface) was computed using the  $x_i$  and  $y_i$  co-ordinates of each vertex and applying the following equation (Husch et al., 1982):

$$C_s = \left( \frac{\sum x_i(y_{i-1} - y_{i+1})}{2} \right)$$

In contrast with the previous parameters, live crown length was measured after each tree was felled. Live crown length was obtained subtracting the height of the first live whorl (i.e. when more than half branches were alive) from the total height. Then, the live crown was divided into three strata of equal length to estimate the leaf area using ratio estimators in stratified random sampling (Ross, 1981; De Vries, 1986; Norman and Campbell, 1989; Daughtry, 1990; Gower and Norman, 1991). All branches in each stratum were removed and their fresh weight ( $P_i$ ) was measured with a precision of 0.05 kg.

The leaf area for each stratum ( $LA_i$ ) was estimated from the mean ratio of needle dry weight to branch fresh weight ( $q_i$ ) and the mean specific leaf area

( $SLA_i$ ), using the equation:  $LA_i$  equals  $P_i$  times  $q_i$  times  $SLA_i$ . These means were obtained from three randomly selected branches per stratum.

Within each selected branch, all shoots were removed and weighed. The ratio of needle dry weight to branch fresh weight ( $q$ ) was obtained by selecting 20 shoots and measuring their fresh weight and the dry weight of the needles after drying them at 85°C for 24 h. The values thus obtained were subjected to a linear regression analysis to check that the ratio of dry needle weight to fresh shoot weight was a constant (i.e., a true ratio estimator). This ratio was multiplied by total fresh weight of the shoots within a branch to obtain the dry weight of the needles by branch. Subsequently  $q$  was calculated.

To estimate  $SLA_i$ , within each branch by stratum, 2 g of fresh needles were randomly selected. Their projected leaf area was measured using a scanner and digital image analyzer software (Data Translation, 1993). The dry weight of the sample was measured to compute  $SLA$  by branch. Then the  $SLA_i$  was the average of  $SLA$  of three branches.

#### 2.1.2. Direct estimate of the leaf area in May '97

The difference between the measurements in 1997 and the method used in 1996 regards  $P_i$  and  $q_i$ . In the improved method,  $P_i$  is now the total fresh weight of all shoots of the  $i$  stratum, whereas  $q_i$  is now the ratio dry needle weight of each shoot to the fresh weight of the intact shoot. The  $SLA_i$  was obtained as in 1996 except that all needles of five randomly selected shoots were chosen per stratum.

In both years the computed  $SLA$  was the projected leaf area per gram of leaf dry mass. Thus, to obtain the one-sided area estimate, the projected needle area has to be multiplied by factor 1.285 (equals to  $\pi/4 + 1/2$ ). This factor is based on the assumption that the Aleppo pine needles constitute an hemi-cylinder (since there are two needles per fascicle and, according to Johnson (1984), together they resemble a cylinder).

Because some authors have argued that  $SLA$  might depend upon needle age, we checked that this ratio was a constant within a stratum for this species. Leaf area of live crown ( $L_t$ ) and LAI of the tree ( $L_{td}$ ) were computed using the following equations:

$$L_t = \sum LA_i; \quad L_{td} = L_t / C_s; \\ i = \text{stratum number 1, 2 and 3.}$$

In order to obtain the correction factors applicable to LAI-2000 results (as a result of the amount of supporting woody material in the canopy and also the clustering of needles in shoots (Chen, 1996)), we estimated for the eight selected individuals in 1997, one half of the total wood surface in the crown and the ratio one-sided area of needles of shoot to the half of shoot area.

To estimate the first parameter, i.e. one half of the total surface of the crown branches ( $W$ ), all the branches within each section were classified according to their diameter at the insertion point with the stem in 1 cm width classes. All branches within each class were counted and weighed. One branch representative of each class was selected to measure base diameter, length and number of second order branches. Three branches were chosen from all second order branches, one in the lower part, another one in the middle, and a third one in the top of the main branch, to measure, as in the previous case, base diameter, length and number of third order branches. A representative branch was chosen from all third order ones, and its length and base diameter was measured. If we consider the branches (be they first, second or third order ones) as cone-shaped geometric bodies, one half of the total branch surface can be calculated as  $\pi/2$  of the projected area by the branches. Then, the correction factor due to the proportion of the area of branches to the total of branches plus needles ( $\alpha$ , Chen, 1996) was calculated as  $\alpha = W/(W+L)$ , where  $L$  is one-sided needle area.

To compute the second correction factor to the LAI-2000 measurements (Chen, 1996), i.e. the within-shoot clumping ( $\gamma_e$ ), five shoots per stratum were selected at random. A video camera system was used to measure, for each shoot, the projected area ( $A_p$ ) at three angles (0, 45 and 90°), keeping the shoot horizontal, and computing half of the total shoot surface ( $A_s$ ) according to simplified formula by Chen (1996):

$$A_s = 2 \times \frac{A_p(0^\circ) \times \cos(15^\circ) + A_p(45^\circ) \times \cos(45^\circ) + A_p(90^\circ) \times \cos(75^\circ)}{\cos(15^\circ) + \cos(45^\circ) + \cos(75^\circ)}$$

The needles of each shoot were later removed from the axis to measure the one sided area ( $A_n$ ). Then, the correction factor ( $\gamma_e$ ) was computed as  $A_n/A_s$ .

To estimate forest stand parameters and allometric relationships, the volume, dry biomass and sapwood areas of the stem of subject trees were calculated using a stem analysis. The stem was chopped and weighed in logs of 1 m in length. A 2 cm thick slice was cut from the lower end of each log. To carry out the stem analysis, the following parameters were measured on each slice: diameter with and without bark, total area, sapwood area, the number and radius of rings. The analysis was carried out using TDIF 2.0 software (Bengoa, 1996). The moisture content of each slice was measured after drying it at 105 °C for 48 h and measuring subsequently the dry stem biomass.

## 2.2. Direct estimate of stand LAI (Allometric estimate)

The stand LAI is defined as total foliage area per unit of ground surface area (Watson, 1947). Several authors have calculated the foliage area either as half the total surface area of foliage (termed one sided foliage area, Anderson, 1971; Norman and Welles, 1983; Chen and Black, 1992a, b) or as largest projected leaf area (Whitehead, 1978; Gower and Norman, 1991). As we did with LAI of individual trees, stand LAI definition used was the one-sided leaf area. This was used since one sided foliage is what is estimated when foliage area is computed by means of radiation measures and, in addition, the projected leaf area has neither physical nor biological significance (Chen and Black, 1992b).

To obtain estimates of direct stand LAI ( $L_{\text{STAND}}$ ) that can be used as a reference with two different strategies to estimate indirectly the LAI (standard -transects- and the non-standard, using the LAI-2000, see Section 2.3), two sampling procedures were carried out: the first one consisted in choosing 12 circular plots of 10 m radius, in which the non-standard indirect method would be conducted; the centre of each plot was one of the trees previously selected for felling; a radius of 10 m was selected because a plot of this size includes all the trees that can be potentially seen by the LAI-2000; the second consisted in a sampling procedure using 10 rectangular plots

Table 1  
Allometric relationships in *Pinus halepensis* (Mill.)<sup>a</sup>

Model	$R^2$ (%)	SEE
$B=0.21D^2$	98.8	14.58
$V=0.117D^{2.398}$	95.5	0.19 <sup>b</sup>
$C_c=0.067D^{1.661}$	89.6	0.22 <sup>b</sup>
$C_c=0.017D^{1.715}e^{0.074I_s}$	93.5	0.17 <sup>b</sup>
$B_{RA}=0.011D^{2.38}$	81.4	0.46 <sup>b,c</sup>
$L_t=0.054D^{2.05}$	85.6	0.31 <sup>b</sup>
$L_t=0.107D_{wb}^{1.98}$	90.2	0.27 <sup>b</sup>
$L_t=0.141S_{ac}^{1.11}$	91.9	0.24 <sup>b</sup>
$L_t=0.152S_{abh}^{1.00}$	90.5	0.26 <sup>b</sup>
$L_t=0.127D_c^{2.05}$	87.1	0.30 <sup>b</sup>
$L_t=0.134D_{cwb}^{2.08}$	89.9	0.27 <sup>b</sup>

<sup>a</sup> Results of model fitting.  $D$  (DBH, diameter at breast height, cm),  $D_{wb}$  (DBH without bark, cm),  $D_c$  (diameter at the base of the live crown, cm),  $D_{cwb}$  (diameter without bark at the base of the live crown, cm),  $L_t$  (leaf area, m<sup>2</sup>),  $H$  (total height, m),  $V$  (stem volume, dm<sup>3</sup>),  $B$  (dry biomass of tree stem, kg),  $S_{ac}$  (sapwood area at the base of the live crown, m<sup>2</sup>),  $S_{abh}$  (sapwood area at breast height, m<sup>2</sup>),  $B_{RA}$  (projected branch area, m<sup>2</sup>),  $C_c$  (crown coverage, m<sup>2</sup>);  $I_s$  (spacing index);  $n=20$ ,  $p<0.001$ , normal distribution of residuals, residual average=0.

<sup>b</sup> Logarithmic units.

<sup>c</sup>  $n=8$ .

measuring 20 m × 60 m (with its longest axis pointing northwards), where the standard indirect LAI estimate was measured (transects). Tree location in relation to centre of the plot (distance and azimuth) and their DBH were measured in all trees within each one of the 22 plots. The allometric relationship between leaf area and DBH had to be calculated in order to obtain the leaf area in each plot (Table 1). Because the trees used to define such allometric relationship were felled at different times, an allometric relationship was defined for each date and then we checked that there were no significant effects of date.

To obtain  $L_{\text{STAND}}$  by plot, leaf area by plot was divided by the plot area. Basal area per ha ( $B_A$ ) and number of trees per ha ( $N$ ) were also measured. Crown coverage in percentage ( $C_c$ ), stem volume per ha ( $V$ ) and dry biomass per ha ( $B$ ), were estimated using the allometric relationships shown in Table 1.

## 2.3. Indirect estimate of the LAI-STAND, using the LAI-2000

The indirect estimates were carried out with two different strategies:

1. using a systematic sampling strategy (standard strategy) within each of the 10 rectangular plots, sampling at 2 m intervals (26 points) in a transect along the longest axis; three measurements were taken at every point (readings  $B_e$ , below canopy) which were oriented at W, N and E, respectively, and using a 90° view-cap. Each of these was repeated three times to increase its consistency. The sensor was placed at 1.3 m above ground. The readings were taken from 19 December 1996 to 13 January 1997, using two LAI-2000 units in remote mode.
2. Using the LAI-2000 in the 12 circular plots before each tree was felled with a non-standard method consisting of placing the sensor next to tree stem (15 cm), always hiding the stem (using view-caps) and at 1.30 m above ground. Eight different protocols were used in this non-standard strategy. These protocols were developed from pilot experiments suggesting the influence of two additional factors in LAI-2000 estimations: (a) sensor height, since the amount of tree elements included in the sensor field of view seemed to depend upon the height of the measure and since the LAI-2000 estimations have been shown to depend on stand height (Moser et al., 1995); (b) the gap distribution, which is not uniform either within tree crown or within canopy. LAI-2000 estimates are proportional to the logarithm of the gap fraction, averaging multiple readings below canopy,  $B_e$ , (average of logarithms) before storing a single value in a file. However, each individual  $B_e$  reading is a linear average of the radiation from whatever azimuthal view range the sensor can see, as determined by the view cap. If the sensor sees dense foliage in one direction and little or no foliage in another direction at the time a  $B_e$  reading is recorded, then the gap in the canopy will be over weighed and LAI will be underestimated (Li-Cor, 1991a). To avoid this problem we used different view caps with different  $B_e$  readings in a file. The eight protocols are the result of a factorial experimental design (repeated measures subjecting each one of the 12 plots used to every treatment, Neter et al., 1996) with the two factors previously mentioned, i.e. to two different heights — 1.3 m above ground (1) and to 2 m below live crown (2) — and four different combinations of view-cap and  $B_e$  readings: (A) placing a 270° view-cap and taking

a  $B_e$  reading orienting the device southwards, (B) placing a 270° view-cap and taking  $B_e$  readings every 180° starting by north orientation, (C) placing a 180° view-cap and taking  $B_e$  readings every 120° starting by north orientation and (D) placing a 90° view-cap and taking  $B_e$  reading in the four cardinal points (Fig. 1). All  $B_e$  readings were repeated three times and taken in the same compass direction as readings above canopy ( $A_b$ ), according to protocols. The same LAI-2000 unit was used in all measurements. Readings ‘above canopy’ were taken in an open area whose radius was more than three times greater than the stand height, and using the same view-cap that was used for  $B_e$  readings. The readings were taken from the 17–31 January 1996, always under uniform overcast (cloudy day), at sunset or sunrise. Protocol order was randomised. Subsequently, LAI-2000 measurements were recomputed using the C-2000 software (Li-Cor, 1991b) to ignore selected rings.

Because the size of the crown at the plot center might affect the LAI-2000 measurements, we carried out an analysis of variance to test whether this affected indirect stand LAI estimates. For this analysis, the 12 plots used in the non-standard strategy were classified (cluster analysis) in three size groups (small, medium and large) according to the size (crown surface, crown length and DBH) of the trees placed in their centre under which the sensor of the LAI-2000 was placed. Cluster Number 3 included only Plot 9 (with a large tree in its centre) and was, thus, discarded due to the low  $L_{\text{STAND}}$  and  $B_A$ , hence leaving the classification with only two clusters (the first one consisting of four large trees and the second one consisting of seven small trees). A post hoc analysis checked that the mean  $L_{\text{STAND}}$  of the plots where subject were trees, did not differ between both groups.

Estimates of  $L_{\text{STAND}}$  were compared to those obtained with LAI-2000 using different protocols. Some selected rings were eliminated to examine which method yielded the highest correlation with  $L_{\text{STAND}}$ .

The validity of the sampling strategy (non-standard) and protocols used for indirect LAI estimates were corroborated in eight additional circular plots (May 1997). The  $L_{\text{STAND}}$  was calculated using the earlier mentioned allometric relationship and compared to LAI-2000 values obtained with the most efficient

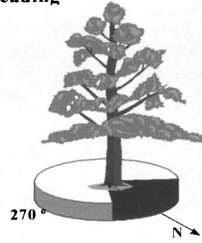
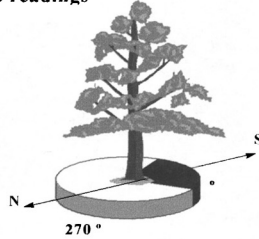
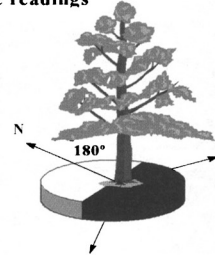
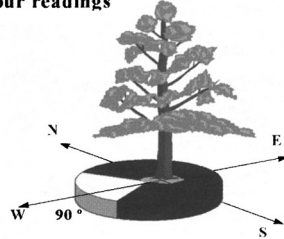
**A: Using a 270° View Cap and taking one reading****B: Using a 270° View Cap and taking two readings****C: Using a 180° View Cap and taking three readings****D: Using a 90° View Cap and taking four readings**

Fig. 1. Protocols to measure with the LAI-2000 in the non-standard strategy. The view-cap hides the operator and the stem of tree. The sensor was placed at two heights: 1.3 m above ground and 2 m below live crown and with four different combinations of view-cap and  $B_e$  readings: (A) placing a 270° view-cap and taking a  $B_e$  reading orienting the device southwards, (B) placing a 270° view-cap and taking  $B_e$  readings every 180° starting by north orientation, (C) placing a 180° view-cap and taking  $B_e$  readings every 120° starting by north orientation and (D) placing a 90° view-cap and taking  $B_e$  reading in the four cardinal points.

protocol and the empirical corrector coefficient estimated. Subsequently, an analysis tested whether mean  $L_{\text{STAND}}$  estimates and mean LAI-2000 corrected values were significantly different.

### 3. Results and discussion

#### 3.1. Direct estimate of the LA and LAI of individual trees

The dendrometric characteristics and the direct estimate of the LAI of individual trees,  $L_{\text{td}}$ , are shown in Table 2. The mean LAI of the 20 trees was 2.69 ( $\text{m}^2/\text{m}^2$ ), ranging from 1.50–4.58. A  $t$ -test showed that there were no significant differences ( $p=0.78$ ) between the means of  $L_{\text{td}}$  of the two tree groups used as a sample. There does not seem to exist published data regarding the LAI of Aleppo pine trees nor that of other pine species which means that, unfortunately, no comparisons can be made. We could only compare our results with individual trees of *Fraxinus excelsior* L., which has a LAI ranging between 1.93–6.65 (Le Goff and Ottorini, 1996).

The results corresponding to both proposed methodologies for LA estimate of individual trees (both that used in 1996 and that used in 1997), using ratio estimators in stratified random sampling (De Vries, 1986) showed that the relative sampling errors, at the 95% probability level, were of different magnitude. When the ratio estimator was the needle dry weight to fresh branch weight and the population total was the fresh weight of the branches per stratum (methodology used in January 1996), then the relative sampling error ranged between 6.95% (Tree No. 12) and 60.33% (Tree No. 5). In contrast, when the ratio estimator was dry needle weight to fresh shoot weight, and the population total was the fresh shoot weight per stratum (methodology used in May 1997), then the relative sampling error ranged between 1.03% (Tree No. 7) and 3.36% (Tree No. 3).

There was a weak significant dependence between direct LAI of individual tree ( $L_{\text{td}}$ ) and dendrometric parameters ( $p>0.03$ ). However, if the number of individuals per ha with  $\text{DBH}>7.5$  cm ( $N$ ) is included in the models, then a significant correlation was found:

$$L_{\text{td}} = 2.69 + 0.045D - 0.0016N$$

Table 2  
Summary of dendrometric characteristics of sampled trees

Tree No.	January 1996			Tree No.	May 1997		
	DBH <sup>a</sup> (cm)	Ht <sup>b</sup> (m)	$L_{td}$ <sup>c</sup> (m <sup>2</sup> /m <sup>2</sup> )		DBH (cm)	Ht (m)	$L_{td}$ (m <sup>2</sup> /m <sup>2</sup> )
1	36.6	12.6	2.66	1	28.5	13.5	3.14
2	29.6	11.9	3.62	2	21.5	11.1	3.43
3	31.2	12.9	2.22	3	29.2	12.3	3.49
4	19.7	9.8	2.39	4	20.2	10.4	1.61
5	21.6	10.8	4.58	5	25.5	11.3	3.59
6	17.5	9.6	1.82	6	14.4	10.4	1.50
7	28.8	12.0	2.80	7	12.5	9.0	1.96
8	18.7	8.1	1.91	8	16.7	12.3	2.33
9	25.7	11.4	3.69				
10	8.9	5.8	2.61				
11	18.1	9.6	2.45				
12	10.8	7.4	2.11				

<sup>a</sup> DBH: diameter at breast height (1.30 m).

<sup>b</sup> Ht: total height.

<sup>c</sup>  $L_{td}$ : direct estimates of the leaf area index of individual trees.

where  $D$  is the DBH,  $R^2=28\%$ ,  $SEE=0.69$ ,  $p=0.02$ ,  $n=20$ . There was also a significant dependence between  $L_{td}$  and the modified neighboring trees competition index ( $C_i$ , Avery and Burkhart, 1983):

$$C_i = \sum_{j=1}^z \frac{D_j/D_i}{l_{ij}}$$

where  $C_i$ =competition index of  $i$ th subject tree,  $D_i$ =DBH of  $i$ th subject tree,  $D_j$ =DBH of  $j$ th competitor tree,  $l_{ij}$ =distance between subject tree  $i$  and  $j$ th competitor,  $z$ =number of competitors placed within the plot. The model is:

$$L_{td} = 3.62 - 0.297C$$

where  $R^2=29\%$ ,  $SEE=0.695$ ,  $p<0.01$ , normal distribution of residuals, residual average=0,  $n=20$ . This suggests that high stocking densities may cause low projected crown area of each individual but, at the same time, it would be likely to decrease the leaf area in the live crown in a greater extent than the previous variable decreasing, thus, the  $L_{td}$  of individual pines.

In agreement with Shinozaki et al. (1964a, b) and Waring et al. (1982), we found that sapwood area in the basal live crown was the parameter with the highest correlation with leaf area of live crown ( $R^2=91.86\%$ ,  $SEE=0.24$ ,  $p<0.001$ ,  $n=20$ ), although

other parameters such as sapwood area at breast height, diameter with and without bark in the basal live crown and DBH both with and without bark, were also highly correlated (Table 1).

To derive the leaf area, we propose two allometric relationships (Fig. 2): one for the individuals felled in January 1996 and another for those felled in May 1997. However, although results suggest that the allometric relationship tends to differ depending on the date of data collection, a comparison between the regression lines to test for statistically significant differences between the intercepts and slopes (Statgraphics, 1997), showed that they did not differ (intercepts,  $F$ -ratio=3.83,  $p=0.068$ ; slopes,  $F$ -ratio=1.72,

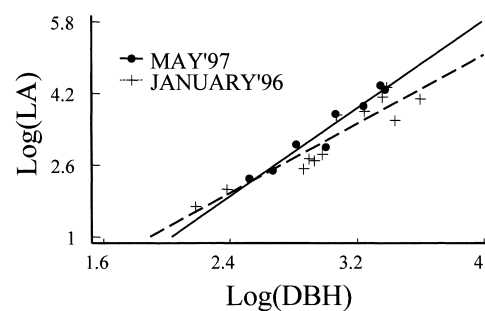


Fig. 2. Leaf area by tree (LA, m<sup>2</sup>) vs diameter at breast height (DBH, cm) obtained on two dates, January 1996 ( $n=12$  trees) and May 1997 ( $n=8$  trees).

$p=0.2085$ ). Hence, the following relationship is proposed:

$$L_t = 0.0536D^{2.05}$$

where  $L_t$  is the leaf area of individual tree ( $m^2$ ) and  $D$  is the DBH ( $cm^2$ ),  $R^2=85.53\%$ ,  $SEE=0.31$  — logarithmic units,  $p<0.001$ ,  $n=20$ , normal distribution of residuals, residual average=0. This allometric relationship was used to estimate the leaf area of the 22 plots (see further).

Although both relationships are not significantly different, further experiments suggest that the relationship would vary with date of data collection as a result of different weather or seasonal conditions affecting the trees (López-Serrano, unpublished data). This hypothesis is coherent with the results obtained by Cutini (1996) in Turkey oak (*Quercus cerris* L.) forest stands, where different climatic conditions affect canopy properties. Also, this coincides with the temporary variability of the SLA and mean weight of the crown shoots. A multifactor ANOVA showed that the SLA of the needles varied with the date of data collection and the place of the needles within the tree crown. Tree size, in contrast, was not a significant factor. The SLA (one-sided leaf area,  $cm^2/g$ ) had a mean $\pm$ SE ranging from  $28.12\pm0.35$  ( $n=36$ ) in January 1996 to  $31.75\pm0.43$  ( $n=24$ ) in May 1997. The lower crown third achieved values higher than the top crown section, and 1997 values were also higher than those of 1996 (29.3 versus 26.9 and 32.0 versus 31.5 in January 1996 and May 1997, respectively). A similar result was found in *P. sylvestris* (Rey, 1993) and in *Fagus sylvatica* (Bartelink, 1997). Results also show that the mean fresh weight of the shoots and that of the shoot needles (once removed) recorded in May 1997 was greater than that recorded the previous year ( $p<0.001$ ), with the top third of the crown showing the heaviest shoots.

We found a relationship between the leaf area of an individual tree ( $L_t$ ) and both DBH ( $D$ ) and the spacing index  $I_s$  (cited in Assmann, 1970) and defined as

$$I_s = \left[ \frac{(\pi C_s)}{(4B_A)} \right]^{0.5}$$

The relationship was:

$$L_t = 0.014D^{2.103}e^{0.07(I_s)}$$

where  $L_t$  in  $m^2$ ,  $D$  in  $cm$ ,  $R^2=87.61\%$ ,  $SEE=0.29$  — logarithmic units,  $p<0.001$ ,  $n=20$ , normal distribution of residuals, residual average=0. This model shows a positive correlation of  $L_t$  with  $D$  and  $I_s$ . When  $I_s$  reaches its maximum, then maximum leaf area is obtained. This model proves the influence of forest stand characteristics in the  $L_t$  of the individual tree and is coherent with that relating the  $L_{td}$  with stand density or with the modified neighbouring trees competition index. For this reason, allometric relationships might be an inaccurate estimator of stand LAI, as such relationships depend on the competition level experienced by measured trees within the stand. It might be even worse to extend allometric relationships obtained from a particular stand to stands that might be growing under different ecological conditions (e.g., site index) or applying them in a different moment to that for which they were defined (change in weather conditions, i.e., seasonal variability).

The relationships used to estimate forest mensurational parameters (dry stem biomass, volume of the stem with bark, crown coverage and projected branch area) are shown in Table 1.

### 3.2. Direct (allometric) estimate of LAI-stand

In Aleppo pine, the LAI by plot obtained using the allometric relationship for all trees within a plot ( $L_{stand}$ ), ranged from 0.26 to 1.67, being smaller than that in other pine species (see Gower and Norman, 1991; Deblonde et al., 1994; Sampson and Allen, 1995).

The  $L_{stand}$  in circular plots (mean $\pm$ SE,  $n=12$ ) obtained by sampling was  $1.15\pm0.11 m^2/m^2$ . In rectangular plots, the results were  $1.33\pm0.08 m^2/m^2$  ( $n=10$ ). Although the  $L_{stand}$  obtained with  $20 m \times 60 m$  plots appears to be slightly higher, a comparison of mean values belonging to both samples showed that there were no significant differences ( $t=1.302$ ,  $p=0.209$ ). The difference between values might be due to the unequal plot size in both samples, which results in a different estimate of the mean diameter distribution of experimental plot (25 ha) (García, 1992). Similarly, the mean values of forest stand parameters ( $N$ ,  $B_A$ ,  $H$ ,  $C_c$ ,  $B$ ,  $V$  and BAI (branch area index) see Table 3), do not differ significantly in both samplings.

Table 3

Summary of stand attributes (Mean $\pm$ SE), obtained by plot sampling, including (With) or not (Without) small trees (DBH<7.5 cm) with both, circular ( $n=12$ ) and rectangular ( $n=10$ ) plots

		$C_c(\%)^a$	$N(\text{trees/ha})^b$	$BA(\text{m}^2/\text{ha})^c$	$H(\text{m})^d$	$B(\text{kg/ha})^e$	$BAI(\text{m}^2/\text{m}^2)^f$	$V(\text{m}^3/\text{ha})^g$
Circular	With	40.3 $\pm$ 3.7	1093 $\pm$ 134	14.4 $\pm$ 1.4	8.5 $\pm$ 0.4	34705 $\pm$ 3538	0.648 $\pm$ 0.066	61.2 $\pm$ 6.2
	Without	36.6 $\pm$ 3.6	522 $\pm$ 56	13.8 $\pm$ 1.4	10.3 $\pm$ 0.2	33734 $\pm$ 3453	0.631 $\pm$ 0.065	59.4 $\pm$ 6.1
Rectangular	With	52.9 $\pm$ 3.3	812 $\pm$ 87	16.8 $\pm$ 1.0	9.8 $\pm$ 0.3	40230 $\pm$ 2218	0.760 $\pm$ 0.042	75.6 $\pm$ 4.3
	Without	50.4 $\pm$ 3.2	601 $\pm$ 54	16.3 $\pm$ 1.0	10.3 $\pm$ 0.2	39518 $\pm$ 2210	0.745 $\pm$ 0.042	74.2 $\pm$ 4.3

<sup>a</sup>  $C_c$ : crown coverage.

<sup>b</sup>  $N$ : number of trees.

<sup>c</sup>  $BA$ : basal area.

<sup>d</sup>  $H$ : mean quadratic height.

<sup>e</sup>  $B$ : stem dry biomass.

<sup>g</sup>  $V$ : stem volume.

<sup>f</sup>  $BAI$ : branch area index (one sided area).

A very high correlation was found between leaf area ( $L_A$ ) and basal area ( $B_A$ ) by plot:

$$L_A = 792B_A$$

where  $L_A$  in  $\text{m}^2/\text{ha}$  and  $B_A$  in  $\text{m}^2/\text{ha}$ ,  $R^2=99.9\%$ ,  $SEE=114 \text{ m}^2/\text{ha}$ ,  $n=22$ ,  $p<0.001$ , normal distribution of residuals, intercept not significant, residual average= $6.4 \text{ m}^2/\text{ha}$ . This result suggests that a quick estimate of the stand LAI may be computed using basal area values as long as climatic conditions of the study area remain stable and, thus, the allometric relationship used to estimate  $L_A$  remains valid. However, the high correlation obtained might have arisen from the use of allometric relationships to estimate  $L_A$ , as there is a functional relationship between the basal area of an individual and its DBH.

### 3.3. Indirect estimate of the LAI-stand, using the LAI-2000

Table 4 shows the summary of LAI-2000 measurements obtained with the non-standard procedure and using the eight different protocols. We found that neither the sensor height nor view-cap used and  $B_e$  readings combination affect mean LAI-2000 estimates ( $F\text{-ratio}<1.4$ ,  $p>0.10$ ). In a study of LAI indirect estimation carried out in *P. pinea* L., using the same methodology (López-Serrano, unpublished data), results were affected by sensor height, with increasing LAI-2000 estimates the higher the sensor was placed (always below crown). In Aleppo pine, results from

measures taken at both heights might be similar because, as a consequence of high relative crown length, Position 1 and 2 were very similar (1.77 m is the mean distance between 1 and 2 positions).

Although there were no significant differences among the protocols used in the non-standard procedure, the best correlation between  $L_{\text{STAND}}$  and the LAI-2000 measurement was obtained when the sensor was placed 1.3 m above ground and  $B$  protocol was used (using a  $270^\circ$  view-cap and taking a  $B_e$

Table 4

Summary of LAI-2000 measurements (Mean $\pm$ 1SD,  $n=12$ ) with the non-standard sampling using different protocols and computing the LAI using the five rings of the sensor ( $L_{2000(1-5)}$ )

Protocol <sup>a</sup>	$L_{2000(1-5)}$
1A	1.20 $\pm$ 0.38
1B	1.18 $\pm$ 0.29
1C	1.06 $\pm$ 0.24
1D	1.16 $\pm$ 0.26
2A	1.31 $\pm$ 0.37
2B	1.21 $\pm$ 0.23
2C	1.10 $\pm$ 0.20
2D	1.18 $\pm$ 0.33

<sup>a</sup> The first character indicates the height of the sensor: 1, at 1.3 m above ground; 2, at 2 m below live crown. The second character indicates the type of view-cap used and the number of readings carried out: (A) placing a  $270^\circ$  view-cap and taking a  $B_e$  reading orienting the device southwards, (B) placing a  $270^\circ$  view-cap and taking  $B_e$  readings every  $180^\circ$  starting by north orientation, (C) placing a  $180^\circ$  view-cap and taking  $B_e$  readings every  $120^\circ$  starting by north orientation and (D) placing a  $90^\circ$  view-cap and taking  $B_e$  reading in the four cardinal points.

Table 5

Regression coefficients (slopes) of the LAI-*STAND* ( $\text{m}^2/\text{m}^2$ ) models versus LAI-2000 measures, for two sampling strategies: standard ( $n=10$ ) and non-standard ( $n=12$ )<sup>a</sup>

Sampling strategy	LAI-2000	Slope (parameter $\pm$ SE)	$R^2$ (%) ( $R^2$ with intercept)	SEE
Standard <sup>b</sup>	$L_{2000(1-5)}$	$1.027\pm0.027$	99.4 (79.8)	0.11
	$L_{2000(2-5)}$	$1.029\pm0.028$	99.2 (74.3)	0.13
	$L_{2000(1-4)}$	$0.967\pm0.029$	99.3 (79.7)	0.11
Non-standard <sup>c</sup>	$L_{2000(1-5)}$	$0.996\pm0.042$	98.1 (82.9)	0.17
	$L_{2000(2-5)}$	$1.035\pm0.047$	97.8 (76.5)	0.19
	$L_{2000(1-4)}$	$0.901\pm0.032$	98.7 (85.0)	0.15

<sup>a</sup> The models were proposed using all the rings in the LAI-2000 ( $L_{2000(1-5)}$ ), discarding the most zenithal one ( $L_{2000(2-5)}$ ), or the most horizontal one ( $L_{2000(1-4)}$ ). All intercepts were not significant ( $p>0.1$ ), significant models ( $p<0.001$ ), normal distribution of residuals, residual average=0.

<sup>b</sup> Standard strategy:  $n=26$  point sampling by plot, the sensor was placed at 1.30 m above ground with a  $90^\circ$  view-cap; three measurements were taken in each point, repeated three times, oriented W, N and E.

<sup>c</sup> Non-standard strategy:  $n=1$  point sampling by plot; the sensor was placed 1.30 m above ground, using  $270^\circ$  view-caps to hide the stem; two readings were taken per point, repeated three times, oriented N and S.

reading northwards and another southwards). The model proposed, using all rings ( $L_{2000(1-5)}$ ) was:

$$L_{\text{STAND}} = 0.996L_{2000(1-5)}$$

where  $R^2=98.07\%$  — statistic with the intercept=82.92%, SEE=0.17,  $p<0.001$ , normal distribution of residuals, residual average=0.002, intercept not significant ( $p=0.88$ ,  $n=12$ ). Nevertheless, the maximum correlation is achieved computing the LAI without the outer ring (i.e. without the  $68^\circ$  ring,  $L_{2000(1-4)}$ ), although then the LAI-2000 overestimates the  $L_{\text{STAND}}$  (Table 5). This result agrees with that of Cescatti (1997) showing that in heterogeneous stands an underestimate of the transmittance occurs in the 5th ring ( $60\text{--}74^\circ$ ), which may be due either to the clustering of branches in whorls (clustering at a level higher than shoots) which results in an increase in gaps at large zenith angles or to the blue radiation scattered by conifers at large zenith angles. For this reason, when this ring is discarded from the analysis, there is an improvement in the results, but these are then overestimated as a result of the position of the sensor under the tree crown. Only if the most zenithal ring is discarded when computing the indirect LAI (i.e. without the  $7^\circ$  ring,  $L_{2000(2-5)}$ ), the estimate of the  $L_{\text{STAND}}$  is unbiased (intercept=0 and slope=1, Table 5), although the highest correlation is not reached at this point.

A significant and strong correlation was also found when the direct and indirect estimates of LAI are com-

pared using the standard sampling strategy (Table 5). The model proposed, using the five rings, was:

$$L_{\text{STAND}} = 1.027L_{2000(1-5)}$$

where  $R^2=99.4\%$  — statistic without eliminating the intercept=79.8%, SEE=0.11,  $p<0.001$ , normal distribution of residuals, residual average=0, intercept not significant ( $p=0.33$ ,  $n=10$ ).

A comparison of the regression lines obtained with both strategies (standard and non-standard, Fig. 3) showed that there were no significant differences

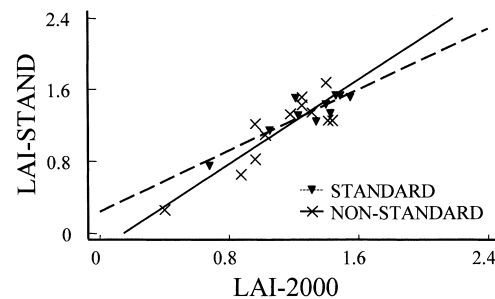


Fig. 3. LAI-*STAND* observed vs predicted, using the LAI-2000 measurements (using all rings) in both, standard and non-standard sampling strategy. Standard strategy:  $n=26$  point sampling by plot, the sensor was placed a 1.30 m above ground and a  $90^\circ$  view-cap; three measurements were taken in each point, repeated three times, oriented W, N and E. Non-standard strategy:  $n=1$  point sampling by plot; the sensor was placed 1.30 m above ground, using  $270^\circ$  view-caps to hide the stem; two readings were taken per point, repeated three times, oriented N and S.

between them (intercepts,  $p=0.44$ ; slopes,  $p=0.12$ ). When in the both strategies the LAI-2000 measures are conducted without considering the most zenithal ring ( $L_{2000(2-5)}$ ) both lines became very similar (Table 5; intercepts  $p=0.99$ ; slopes  $p=0.28$ ), with intercepts not significantly different from 0 and slopes not significantly different to 1; the small differences between regression models may be due, in addition to the strategy used, to range of variation within sample (i.e. in the standard strategy, tree density ranged from 9.3 to 19.1  $\text{m}^2/\text{ha}$  — basal area, whereas in the non-standard one it ranged from 3.2 to 19.8  $\text{m}^2/\text{ha}$ ; for this reason, it is not possible to assess the trend of the data for low values of  $B_A$  in the standard strategy).

In both strategies, when  $L_{\text{STAND}}$  is calculated discarding small individuals ( $\text{DBH} < 7.5 \text{ cm}$ ) then the correlation coefficients improve noticeably. This result might be explained by means of point sampling theory, using a vertical angular count sampling (Hirata, 1955; Bitterlich, 1984), since the probability that a tree is seen by the sensor is proportional to its height. As a consequence, small trees have lower probabilities of being seen by the sensor and, thus, the variable plot generated for these small trees will have a shorter reach (radius). This would not be important if the trees were homogeneously distributed in space, but small trees were distributed in clusters, as a consequence of selective felling carried out 15–20 years ago (see further, Clark-Evans index).

The mean ( $\pm \text{SE}$ ) estimated values for  $L_{\text{STAND}}$  and LAI-2000 measures in the experimental plot (25 ha) using both sampling strategies were:  $1.29 \pm 0.08$  ( $L_{2000(1-5)}$ ) and  $1.33 \pm 0.08$  ( $L_{\text{STAND}}$ ) for the standard strategy ( $n=10$ ); and  $1.12 \pm 0.09$  ( $L_{2000(2-5)}$ , without the 7° ring) and  $1.15 \pm 0.11$  ( $L_{\text{STAND}}$ ) for the non-standard one ( $n=12$ ). In both sampling strategies, the mean values of the  $L_{\text{STAND}}$  and that of the LAI-2000 did not differ significantly ( $t=0.37$ ,  $p=0.72$  and  $t=0.20$ ,  $p=0.84$ , for the standard and non-standard strategy, respectively).

The former results show that for both strategies to be similar, it is necessary to discard the information from the most zenithal ring in the non-standard strategy, since it is this ring which is most influenced by the branches and foliage right above the sensor thus overestimating the  $L_{\text{STAND}}$ . Fig. 4 shows the LAI obtained individually by each of the sensor's rings in each strategy (obtained by data recomputed by C-2000 software;

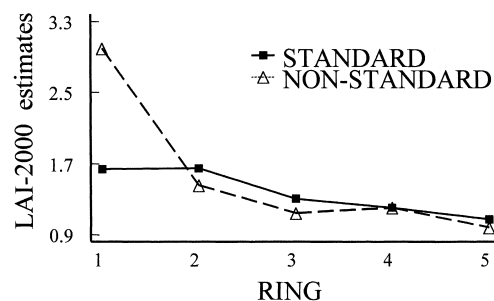


Fig. 4. LAI-2000 measurements by ring, obtained by standard ( $n=78$ , 26 readings-locations by three plots — a plot with low basal area, another one with medium basal area and a third plot with large one) and the non-standard strategy ( $n=12$ ).

Li-Cor, 1991b). In the non-standard strategy, Ring 1 (7°) is the one achieving the greatest value. Table 6 shows the coefficient of variation of LAI ( $\text{CV}(\%)$ ) obtained in each ring. As was expected, standardising the sampling point reduces the variability of the measures, particularly that of the most zenithal ring.

The ANOVA testing whether tree size under which the sensor is placed affects indirect stand LAI estimates ( $L_{2000(1-5)}$ ) showed that this variable did not affect LAI-2000 measurements ( $F=0.001$ ,  $p=0.989$ ). It was previously tested that mean  $L_{\text{STAND}}$  in both groups (small and larger trees) were not significantly different ( $t=0.31$ ,  $p=0.76$ ,  $n=11$ ). These results may have been obtained because in both, small and larger trees, only the 7° ring is completely intercepted by the tree crown above the sensor. In order to prove this, we estimated the sensor angular range that would be intercepted by the crowns in both groups of trees. To do this, the horizontal distance between the sensor and

Table 6

Summary of mean, S.D. and CV (Variation Coefficient) for the LAI-2000 estimates using only one ring each, in the standard and non-standard strategy<sup>a</sup>

Ring	Standard				Non-standard			
	Mean	S.D.	CV(%)	n	Mean	S.D.	CV(%)	n
1	1.636	1.053	64.4	78	2.998	1.122	37.4	12
2	1.644	1.023	62.2	78	1.458	0.641	44.0	12
3	1.304	0.466	35.7	78	1.141	0.459	40.2	12
4	1.202	0.344	28.6	78	1.203	0.451	37.5	12
5	1.076	0.267	24.8	78	0.985	0.216	21.9	12

<sup>a</sup> Ring 1 is the most zenithal one, Ring 5 is the most horizontal.

the edge of the crown was calculated approximately ( $h_L$ , i.e. the radius of the crown ( $\sqrt{(C_s/\pi)}$ ) minus the radius of the stem 1.30 m above ground, minus the distance of the sensor to the stem (0.15 m)) and the vertical distance between the sensor and the bottom of the live crown ( $v_L$ ). The ratio  $k=h_L/v_L$  equals  $\text{tg}(\beta)$ , where  $\beta=\text{arctg}(h_L/v_L)$  is the angle intercepted by the crown.

This ratio was  $0.41\pm0.7$  (mean $\pm$ SD,  $n=4$ ) for the large trees ( $\beta=22.3^\circ$ ) whereas it was  $0.39\pm0.6$  ( $n=7$ ) for the small ones ( $\beta=21.3^\circ$ ), and there were no significant differences between them. Thus a potential ring with a mean angular range of  $\beta=22^\circ$  ( $k=0.40$ ) would be intercepted by the crown in all the measurements (i.e. the  $7^\circ$  ring ( $0\text{--}13^\circ$ ) and part of the  $23^\circ$  ring ( $16\text{--}28^\circ$ ) of the LAI-2000). This is consistent with Fig. 4. In consequence, it is necessary in the non-standard strategy that the sensor is placed at a height such that the former ratio is constant for any site where the sensor is placed. This ratio will show which rings of the sensor are completely intercepted and therefore, which ones should be discarded in the re-computation of the LAI-2000. Thus, the size of the tree under which the LAI-2000 is placed will not introduce any bias in the estimate of the  $L_{\text{STAND}}$ . In our case, this requisite is met placing the sensor 1.30 m above ground.

To check the validity of the non-standard sampling strategy to estimate  $L_{\text{STAND}}$  using the LAI-2000, eight circular plots were selected within the study area (those in whose centre were the trees felled in May 1997). The  $L_{\text{STAND}}$  by plot was calculated using the previously mentioned allometric relationship (Table 1). The LAI-2000 estimations were carried out using a  $270^\circ$  view-cap and taking a  $B_e$  reading northwards and another southwards), computing the LAI without  $7^\circ$  ring. The  $L_{\text{STAND}}$  (mean $\pm$ SD) was  $1.461\pm0.243$  and the LAI-2000 values were  $1.467\pm0.201$  and there were no significant differences with average  $L_{\text{STAND}}$  ( $t=0.06$ ,  $p=0.95$ ,  $n=8$ ). Fig. 5 compares the regression lines of  $L_{\text{STAND}}$  versus LAI-2000 in both dates (January 1996 and May 1997), showing that there are no significant differences between them (intercepts,  $p=0.41$ ; slopes,  $p=0.63$ ). Thus, our sampling strategy allows the quick estimate of the  $L_{\text{STAND}}$  using the LAI-2000. Smith et al. (1993) in forest stands naturally regenerated of Douglas fir, carried out a similar procedure consisting in placing the sensor in

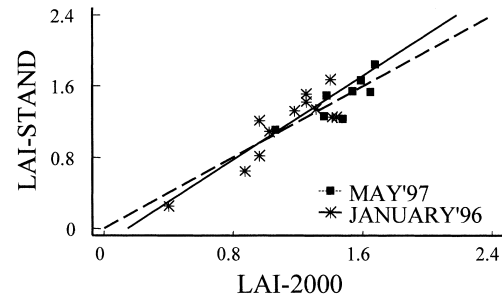


Fig. 5. LAI-STAND vs LAI-2000 measurements obtained by non-standard strategy in January 1996 ( $n=12$ ) and May 1997 ( $n=8$ ), using the  $B$  protocol (i.e. the sensor was placed at 1.30 m above ground and using a  $270^\circ$  view-cap to hide the stem; two readings were taken at each point, repeated three times, oriented N and S; Ring 1 ( $7^\circ$ ) was discarded). There were no significant differences between intercepts ( $p=0.41$ ) or between slopes ( $p=0.63$ ).

the centre of a  $6\text{ m} \times 6\text{ m}$  plot (although not below a tree) and estimating LAI in a single reading in that position. However, this procedure resulted in biased estimates (intercept  $\neq 0$  and slope  $\neq 1$ ).

The mean $\pm$ SE values of the correction factor for clustering of needles in shoots ( $\gamma_e$ , Chen, 1996) are shown in Table 7. An ANOVA showed that there were significant differences between strata ( $p<0.01$ ) but not between individual trees. Thus, and for this date (May 1997) we computed the mean weighed value with shoot weight per stratum, which turned out to be  $0.738\pm0.039$  ( $\pm$ SE,  $n=8$ ). Unfortunately data from

Table 7

Mean values ( $\pm$ SE,  $n=8$ ) of the correcting coefficients due to the clumping of needles in shoots by stratum ( $\gamma_e=A_n/A_s$ ), due to the wood surface (branches+stem in the crown,  $\alpha$ , ratio of total branch in crowns hemi-surface area ( $W$ ) to total foliage hemi-surface area (woody ( $W$ ) and non woody ( $L$ ),  $W+L$ )) in canopy, and the correction factor  $\alpha_1$  (ratio of one-half the total surface area of tree stems —  $w_1$ , measured from 1.3 m above ground to base live crown, to total leaf area (one sided area) plus  $w_1$ ,  $L+w_1$ )

Correction factors (mean $\pm$ SE)

	Stratum	Total canopy	
	$\gamma_e$	$\alpha$	$\alpha_1$
Low	$0.708\pm0.032$		
Medium	$0.726\pm0.051$	$0.489\pm0.007$	$0.039\pm0.0006$
High	$0.825\pm0.049$		

January 1996 were not available and therefore we cannot conclude whether the collection date affects significantly the correction factor.

The correction factor (mean $\pm$ SE) due to the proportion of the area of branches to the total of branches plus needles ( $\alpha$ ) is shown in the Table 7, with no significant differences between plots differing in density (basal area).

The application of these factors to the measures obtained with the LAI-2000 in order to obtain the corrected LAI-2000 ( $L_C$ ) estimates:

$$L_C = L_{2000(1-5)}(1 - \alpha)\gamma_e$$

made the regression between  $L_{\text{STAND}}$  and  $L_C$  poorer ( $R^2=52.5\%$ ,  $\text{SEE}=0.17$ ,  $\text{intercept}=0$ ,  $\text{slope}=2.59$ ,  $n=8$ ). We believe this result can be explained because: (i) the estimate of  $\gamma_e=0.738$  is underestimated because shoot area estimated by means of the video-camera system is overestimated. This may have resulted from the morphological characteristics of the Aleppo pine shoots in semi-arid zones, which consists usually of a relatively large number of needles in open clusters. In consequence, the edge effect of the needles makes the gaps in the shoots smaller or non-existent, thus overestimating the one half of the total shoot area. The correction factor is also effective to compensate the clustering of needles in shoots when the canopy is homogeneous, but does not take into account the error induced by the architecture of the crown, nor the spatial distribution of the trees (Cescatti, 1997); (ii) in natural and artificial forest stands of *P. banksiana*, Deblonde et al. (1994) found that, when the proportion of wood area (one half of the total stem surface area) to foliage area (one sided leaf area) was greater than 19%,  $L_{\text{STAND}}$  was overestimated by LAI-2000. This percentage was 57% in our case, therefore  $L_{\text{STAND}}$  should be overestimated by the LAI-2000. However, as we have seen, the LAI-2000 estimates correctly the  $L_{\text{STAND}}$ . This result can be explained in terms of the low coverage (52.9%) of our stand, which renders the previous argument invalid as a result of the great effect of the spatial distribution of the crowns (crown clumping): the plots used for the non-standard strategy show a trend in their spatial distribution towards clumping; the values of the nearest neighbour statistic  $R$  (Clark-Evans index, cited in Ripley, 1981) range from 0.18 to 0.74 (mean 0.597); also, the plots used in the standard strategy

show a pattern closer to a random one, despite their clumping distribution; their values range from 0.55 to 0.89 (mean 0.736;  $R$  close to 1 correspond to a random distribution, values close to 0 correspond to a clumped one); (iii) depending on the species and crown coverage, tree stem and branches may or may not contribute significantly to the interception of light in forest canopies. The stem under the live crown is not obstructed by any other foliage elements (branches, shoots) and thus must contribute totally to light interception. In contrast, the branches are usually shaded by leaves or shoots, and as a result only a small percentage of branches (<10% for aspen, jack pine or black spruce, Kucharik et al., 1998) contribute to the interception of light in canopies. Thus, if the correction factor  $\alpha_1$  is computed as  $\alpha_1=w_1(L+w_1)$ , where  $w_1$  is the amount of stem hemi-surface area beneath crowns (Table 7), the indirect estimate is remarkably improved compared to the previous correction factor  $\alpha$  ( $R^2=68.0\%$ ,  $\text{SEE}=0.15$ ,  $\text{intercept}=0$ ,  $\text{slope}=1.37$ ,  $n=8$ ). Unfortunately the latest technologies required to compute the effective branch index not masked by shoots were not available at the time of data collection.

The previous paragraphs indicate the complex relationship between canopy architecture and radiative regimes, so that the marked effect of shoot architecture on light penetration in a homogeneous canopy rapidly decreases when the canopy is characterised by other levels of clumping, e.g. crowns (Cescatti, 1998). Thus, further studies are needed in this type of heterogeneous stands to unravel how crown distribution affects indirect estimates.

We also found a very high correlation between indirect estimate of stand LAI and forest stand parameters ( $B_A$ ,  $N$ ,  $B$ ,  $V$  and  $C_C$ ; Table 8). This result is consistent with those of Vose and Allen (1988), who obtained a high correlation between  $L_{\text{STAND}}$  and  $B_A$ , in young forest stands of *P. taeda* L., and Baynes and Dunn (1997), who obtained a significant linear regression between  $B_A$  and LAI-2000 in an 8 year old plantation of *P. elliottii*  $\times$  *P. caribaea*. The results shown in Table 8 were expected because there was a high correlation between  $L_{\text{STAND}}$  and all early forest stand parameters (correlation coefficients greater than 0.85,  $p<0.001$ ) since there is a proportionality between crown and stem biomass of trees (Pardé and Bouchon, 1988).

Table 8

Coefficient of regression models for estimating forest stand parameters (BA,  $N$ ,  $B$ ,  $V$ ,  $C_c$ ) using the LAI-2000 measures (obtained discarding the information from the most zenithal ring —  $7^\circ$ ), for both, standard and non-standard sampling strategy

Dependent variable	Standard			Non-standard		
	Slope	$R^2$ (%) <sup>a</sup>	SEE	Slope	$R^2$ (%) <sup>a</sup>	SEE
BA <sup>b</sup>	13.09	99 (81)	1.41	12.49	98 (81)	2.27
$C_c$ <sup>c</sup>	41.07	99 (84)	4.11	36.13	98 (80)	5.63
$N$ <sup>d</sup>	470.73	98 (65)	97.8	474.89	98 (88)	76.3
$V$ <sup>e</sup>	58.46	99 (75)	7.15	54.97	97 (68)	11.7
$B$ <sup>f</sup>	31014	99 (65)	4500	31173	97 (67)	6770

<sup>a</sup> ( $R^2$  of regression model when intercept is not forced through the origin). Intercepts do not significantly differ from 0 ( $p>0.5$ ). Normal distribution of residuals,  $p<0.001$ .

<sup>b</sup> BA: basal area ( $m^2/ha$ ).

<sup>c</sup>  $C_c$ : crown coverage by plot (%).

<sup>d</sup>  $N$ : number of trees/ha without small trees (DBH<7.5 cm).

<sup>e</sup>  $V$ : stem volume ( $m^3/ha$ ).

<sup>f</sup>  $B$ : stem dry biomass ( $kg/ha$ ).

#### 4. Conclusions

To accurately estimate the leaf area of individual trees, using destructive sampling, it is advisable to use a random stratified sampling with ratio estimators. This should be the dry needle weight to fresh shoot weight and the known population parameter should be the fresh shoot weight per stratum. Thus the sampling errors are very small (1.03–3.36%, at 95% of probability level), although this procedure is labour expensive.

The indirect estimate of  $L_{STAND}$  using the LAI-2000 and the non-standard sampling strategy proposed in this paper was a procedure as effective and accurate as the indirect standard strategy (transects), but more labour-efficient. The indirect estimate of the  $L_{STAND}$  using the LAI-2000, with either strategy was unbiased (intercept $\cong 0$  and slope $\cong 1$ ), although it was not possible in this case to assess the competing and synergizing interactions among the following causes: the effect of needles and shoot clumping, that of the amount of supporting woody material in the canopy and the effect of crown clumping. Nevertheless, the application of the correction factors to avoid the effect of needle clumping into shoots and the effect of the surface of elements non-photosynthetically active did not result in unbiased estimates and had the opposite effect. This might have resulted from characteristics of these stands that have not been considered, such as: (i) the wide gaps between crowns (which requires the appli-

cation of a correction factor to the LAI-2000 measurements to account for non-random spatial distribution of shoots and crowns in the canopy) and (ii) the unaccounted effects of effective canopy branch area that is shaded by shoots and the amount of stem area beneath crowns.

The non-standard sampling strategy proposed consists of using point sampling from a set randomly or systematically distributed in the forest stand (in contrast to a set of points per plot). This point, where the LAI-2000 is placed, must be under a tree crown near the stem (at 15 cm), at a height of at least 2 m from the base of the live tree crown (1.30 m above ground in our case, although in general the height at which the sensor should be placed is that capable of keeping the  $k$ -ratio constant in all the sampling points; this  $k$ -ratio will show us which rings are to be discarded from the recomputation of the LAI-2000). Protocol  $B$  should be used: a  $270^\circ$  view-cap should be used to hide the stem, a  $B_e$  reading should be taken in directions north and south (each repeated three times) and LAI should be computed without the  $7^\circ$  ring. Thus, with our strategy, there should not be important gaps over the reading point (avoiding LAI underestimates) nor will there be stems near the sensor (avoiding thus overestimates of LAI as a result of the stem intercepting radiation) and the overestimation of the LAI as a result of placing the sensor under the tree crown will be minimised when discarding the  $7^\circ$  ring of the recomputation of the LAI-2000 measurements.

Both the standard and the non-standard strategy yielded significant regression models to estimate forest stand parameters, which are labour expensive to measure using direct methods. Thus, the LAI-2000 could be used as a tool to estimate indirectly such parameters. However, our results do not allow to draw any conclusion regarding the need of calibration of the LAI-2000 for this purpose, although a stand level calibration is probably needed.

Significant allometric relationships are proposed to estimate the leaf area of the trees, but results show that such relationships depend on density of the stand (the competition level suffered by the individuals analysed). The spacing index ( $I_s$ ) improves the estimate.

Data collection does not allow us to discern whether weather conditions affect  $L_{\text{STAND}}$  and, consequently, the LAI-2000 measurements. Neither can we know how they affect estimates of forest stand parameters using LAI-2000. The results of this study should, thus, be considered with caution, as the data correspond only to one area within the range covered by the habitat of the Aleppo pine, and our stand is not representative of the entire range of stand densities. For this reason, further experiments might be very interesting, particularly to compare our results with those obtained under different weather and site index conditions. Research is being conducted to address these questions.

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