Review of methods for in situ leaf area index determination, part II: Estimation of LAI, errors and sampling.

M. Weiss[a], F. Baret[b], G.J. Smith[c], I. Jonckheere[d], P. Coppin[d]

[a] NOVELTIS, parc technologique du canal, 2 avenue de l'Europe, 31520 Ramonville-St-Agne, France, seconded to INRA CSE, Avignon, France

[b]INRA CSE, Domaine Saint-Paul, Site Agroparc, 84914 Avignon Cedex 9, France

[c]US Environmental Protection Agency, Region 2, 290 Broadway, New York, NY 10007-1866, USA

[d]Department of land management, Katholieke Universiteit leuven, Vital Decosterstraat 102, 3000 Leuven, Belgium

Correspondence:

Tel : (33) (0)4 32 72 24 23

Fax : (33) (0)4 32 72 23 62

e-mail : marie.weiss@avignon.inra.fr

ABSTRACT

The theoretical background of modelling the gap fraction and the leaf inclination distribution is presented and the different techniques used to derive leaf area index and leaf inclination angle from gap fraction measurements are reviewed. Their associated assumptions and limitations are discussed, *i.e.,* the clumping effect and the distinction between green and non-green elements within the canopy. Based on LAI measurements in various canopies (various crops and forests), sampling strategy is also discussed.

Leaf Area Index/Gap Fraction/ Clumping/Leaf Orientation /Ground measurements/Sampling scheme

1. INTRODUCTION

Canopy structure is characterized by the position, orientation, size and shape of the vegetative elements (Ross, 1981). The distribution of optical properties may also be considered as being part of the canopy structure. Canopy architecture changes with time scales varying from fraction of seconds and minutes (wind, water stresses, …), seasons (phenological evolution, environmental constraints), and years (ecosystem dynamics). An exhaustive and detailed description of canopy structure is not easy due to the large amount of information required. 3D digitisation systems are now available (Sinoquet et al., 1998); but still require a considerable effort to sample all the elements of a representative area of the canopy. Therefore, canopy structure is generally described with only a few variables, such as the leaf area density, and the leaf inclination distribution function (LIDF). The leaf area density is defined as the total one-sided leaf area of photosynthetic tissue per unit canopy volume. The leaf area index, LAI, is then derived by integrating the leaf area density over the canopy height. It corresponds to the one sided leaf area per unit horizontal ground surface area (Watson, 1947). Although this definition is clear for flat broad leaves, it may cause problems for needles and non-flat leaves. Based on radiative transfer considerations, Chen and Black (1992) propose to define LAI as half the total developed area of leaves per unit ground horizontal surface area, which is in agreement with the work of Lang (1991). This definition is therefore valid regardless of the vegetation element shape.

The leaf area index is the main variable used to model many processes, such as canopy photosynthesis and evapotranspiration. It determines the size of the plant-atmosphere interface and thus, plays a key role in the exchange of energy and mass between the canopy and the atmosphere. Moreover, under certain assumptions, knowledge of canopy structure variables (LAI and LIDF) allows the evaluation of the fraction of absorbed photosynthetically active radiation (fAPAR), which is required to model the canopy's photosynthetic activity in a straightforward way (Monteith, 1977). The canopy structure is also critical to the description of the canopy microclimate, which includes wind, temperature and moisture profiles within and above the canopy (Welles, 1990) that not only affect the plant itself; but other living organisms, such as pathogens and insects. We should note that for most applications the LAI refers to the green photosynthetic parts of plants.

Directly measuring canopy structure variables is time-consuming and tedious (Lang et al., 1985) and sometimes destructive to plants, *e.g.* when using a planimeter to measure LAI of detached leaves. A review of the direct LAI measurement techniques is given in Norman and Campbell (1989), Daughtry (1990), Sinoquet and Andrieu (1993), and Jonckeere et al.(this issue). Attempts to directly measure leaf orientation are also performed and two methods are described in Kucharik et al. (1998). An exhaustive sampling of the canopy is generally not possible due to its spatial heterogeneity and thus, the large number of measurements required. Therefore, since the sixties, numerous studies have proposed indirect canopy structure measurements (Welles and Norman, 1991, Welles and Cohen, 1996, Jonckeere et al., this issue). These indirect measurements are all based on the estimation of the contact frequency (Warren-Wilson, 1959) or the gap fraction (Ross, 1981). Contact frequency is the probability that a beam (or a probe) penetrating inside the canopy will come into contact with a vegetative element. Conversely, gap frequency is the probability that this beam will have no contact with the vegetation elements until it reaches a reference level (generally the ground). The term “gap fraction” is often used and refers to the integrated value of the gap frequency over a given domain and thus, refers to the quantity that can be measured. Therefore, measuring gap fraction is equivalent to measuring transmittance at ground level, at wavelengths for which the assumption of black vegetative elements is valid. It is then possible to consider the mono-directional gap fraction, which is the fraction of ground observed in a given viewing direction (or illuminated in a given incident direction). The bi-directional gap fraction is the fraction of soil (or area of a horizontal reference level) which is both illuminated in a given direction and observed in another (Qin and Goel, 1995). When both directions are collinear, the bi-directional gap fraction is equal to the mono-directional gap fraction. This corresponds to the well known ‘hot-spot’ feature observed in the backscattering direction when measuring canopy reflectance; in other words, no shadow except that of the sensor can be observed in this particular geometric condition (Bréon et al., 1997; Gerstl and Simmer, 1986; Kuusk, 1985). This information is therefore of particular importance for remote sensing studies in the solar domain.

The objective of this article is to review the current methods used to estimate canopy structure from gap fraction measurements, mainly focusing on leaf area index and leaf inclination distribution function. The theoretical background of gap fraction and leaf inclination distribution function is described first. Methods to derive leaf area index and leaf inclination angle while considering clumpiness and the distinction between green and non-green canopy elements, as well as the associated assumptions and limitations, are then presented. Finally, attention will be paid to the spatial sampling strategy.

2. THEORETICAL BACKGROUND

2.1. Gap Fraction

2.1.1. General expression

The leaf area density, $l(h)$ at level h in the canopy is defined as the leaf area per unit volume of canopy. The leaf area index, L, at a level H in the canopy is related to the leaf area density through:

$$L = \int_0^H l(h)\, dh \tag{1}$$

Following Warren-Wilson (1959), the mean number of contacts $N(H,\theta_v,\varphi_v)$ between a light beam and a vegetation element at a given canopy level H in the direction (θ_v,φ_v) is given by:

$$N(H,\theta_v,\varphi_v) = \int_o^H G(h,\theta_v,\varphi_v)\, l(h) / \cos\theta_v \, dh \tag{2}$$

Where $G(h,\theta_v,\varphi_v)$ is the projection function, i.e. the mean projection of a unit foliage area at level h in direction (θ_v,φ_v) (see Table 1 for notation). When the leaf area density and the projection function are considered independent of the level h in the canopy, Eq. 2 is simplified into Eq. 3:

$$N(L,\theta_v,\varphi_v) = G(\theta_v,\varphi_v)\, L / \cos\theta_v \tag{3}$$

The projection function is defined as follows:

$$\begin{cases} G(\theta_v,\varphi_v) = \dfrac{1}{2\pi}\displaystyle\int_0^{2\pi}\int_0^{\pi/2} |\cos\psi|\, g(\theta_l,\varphi_l) \sin\theta_l \, d\theta_l \, d\varphi_l & \text{(4a)} \\ \cos\psi = \cos\theta_v \cos\theta_l + \sin\theta_v \sin\theta_l \cos(\varphi_v - \varphi_l) & \text{(4b)} \end{cases}$$

Where $g(\theta_l,\varphi_l)$ is the probability density function that describes the leaf normal orientation distribution function (*i.e.* the fraction of leaf area with a normal within the solid angle $d\Omega_l$, in the direction Ω_l). This introduces the two normalization conditions given in Eq 5a and 5b:

$$\begin{cases} \dfrac{1}{2\pi}\displaystyle\int_0^{2\pi}\int_0^{\pi/2} g(\theta_l,\varphi_l) \sin\theta_l \, d\theta_l \, d\varphi_l = 1 & \text{(5a)} \\ \dfrac{1}{2\pi}\displaystyle\int_0^{2\pi}\int_0^{\pi/2} G(\theta_v,\varphi_v) \sin\theta_v \, d\theta_v \, d\varphi_v = \dfrac{1}{2} & \text{(5b)} \end{cases}$$

Depending on the authors, $g(\theta_l,\varphi_l)$ may also be defined as the leaf angle distribution, *i.e.* the fraction of leaf area for which the angle between the vertical and the normal of the leaf is between θ_l and $\theta_l + d\theta_l$ and the azimuth is between φ_l and $\varphi_l + d\varphi_l$ (Bacour, 2001). In this case, Eq 5a should be written as (Sinoquet and Andrieu, 1993): $\dfrac{1}{2\pi}\displaystyle\int_0^{2\pi}\int_0^{\pi/2} g(\theta_l,\varphi_l)\, d\theta_l \, d\varphi_l = 1$

The contact frequency is a very appealing quantity to indirectly estimate LAI because no assumptions on leaf spatial distribution, shape, and size are required. Unfortunately, the contact frequency is very difficult to measure in a representative way within canopies. This is why the gap fraction is generally preferred. In the case of a random spatial distribution of infinitely small leaves, the gap fraction $P_0(q_v, j_v)$ in direction (q_v, j_v) is related to the contact frequency by:

$$P_0(q_v, j_v) = e^{-N(q_v, j_v)} = e^{-G(q_v, j_v)L/\cos(q_v)} \tag{6}$$

This is known as the Poisson model. Note that the contact frequency is linearly related to LAI, while the gap fraction is highly non-linear with respect to LAI. Nilson (1971) demonstrated, from both theoretical and empirical evidences, that the gap fraction can generally be expressed as an exponential function of the leaf area index even when the random turbid medium assumptions associated to the Poisson model are not satisfied:

$$P_0(q_v, j_v) = e^{-K(q_v, j_v)L} \tag{7}$$

This allows the description of regular leaf arrangement when less than one contact per layer is assumed and clumped arrangement when more than one contact per layer is considered. When the layer thickness tends towards 0, binomial models tend to the Poisson model. An alternative is to use Markov chains to account for the conditional probability of transmission through consecutive layers, assuming that only zero or one contact within a layer is possible (Nilson, 1971). In case of clumped canopies, when the layer thickness tends towards 0 (infinite number of layers), a modified expression of the Poisson model can be derived from the Markov model:

$$P_0(q_v, j_v) = e^{-l_0 G(q_v, j_v)L/\cos(q_v)} \tag{8}$$

Where λ_o is the clumping parameter (λ_o <1). Although not directly derived from theoretical considerations, regular leaf arrangement could be empirically adjusted to Eq. 8 with λ_o >1 (Lemeur and Blad, 1974). The Markov chain model as presented is one of the more flexible models to describe the gap fraction as a function of the number of layers and dispersion index λ_o. However, the directional dependency of λ_o is one of its main difficulties. Evaluation of the relative variance of the gap fraction might aid in solving this problem.

2.1.2. Modelling the leaf inclination distribution function $g(l, q_l, j_l)$

As we previously showed, the gap fraction is related to the leaf area index and the leaf inclination distribution function. Therefore, this function needs to be investigated before focusing on LAI retrieval from gap fraction measurements. The azimuthal variation of the LIDF is often assumed to be uniform, i.e. the probability density function $g(q_l, j_l)$ depends only on the leaf normal zenith angle. This assumption is verified in many canopies; but may be problematic for heliotropic plants like sunflowers (Andrieu and Sinoquet, 1993). Lemeur (1973) has measured the azimuthal distribution of four different plants, showing a nearly random distribution for artichokes and soybeans (except for one direction). He also demonstrated that row crops, like corn, have a propensity for azimuthal directions perpendicular to the rows.

Following Goel (1988), leaf inclination distributions can be divided into six typical functions (Table 2). However, continuous expressions have been proposed to describe the 6 basic distributions, which are convenient when inverting gap fraction models:

1. Beta distribution (Goel and Strebel, 1984): the leaf inclination distribution depends on the gamma function and two parameters, m and n. These parameters are related to the Average Leaf Inclination Angle, ALIA or $\overline{q_l}$, and its second moment, $< q_l^2 >$ (Goel, 1988):

$$\begin{cases} \overline{q_l} = 90n/(m+n) \\ <ql^2> = 90^2 n(n+1)/[(m+n)(m+n+1)] \end{cases}$$

When the assumption of azimuth randomness is not verified, another two-parameter beta distribution can be used (Strebel et al., 1985).

2. Ellipsoidal distribution (Campbell, 1986; Campbell, 1990; Wang and Jarvis, 1988) : leaf inclination distribution is described by the ratio of the horizontal to vertical axes of the ellipse. It can be related to the average leaf inclination angle knowing that $\overline{q_l} = \frac{2}{p}\int_0^{p/2} g(q_l) q_l dq_l$ and that $g(q_l)$ is the probability density function that verifies the normalization condition (Eq. 5).

3. The modified elliptical model of Kuusk (1995): the ellipsoidal distribution is generalized by tilting by a q_m angle (called "modal leaf inclination") towards the main axis of the ellipse. The eccentricity x of the ellipse then determines the shape of the distribution. q_m and x are both related to the mean leaf inclination angle and the variance of the leaf inclination.

These three distributions are significantly different (Bacour, 2001). However, due to the difficulty in accurately assessing the LIDF from gap fraction measurements, the simplest distribution model is generally sufficient. The ellipsoidal distribution is the least complex and flexible distribution since it requires only one parameter whereas the beta and the elliptical distributions require an additional parameter. Furthermore, the ellipsoidal distribution allows for the representation of the unique case of spherical distribution, which is widely used to describe the actual leaf inclination of many canopies. Therefore, in these conditions, the average leaf angle is sufficient to characterize the leaf angle distribution function. However, when considering particular canopies such as row crops or heliotropic plants, it might be worth using more complex models such as the beta distribution (Strebel et al., 1985), which requires four parameters.

2.2. Methods used to estimate leaf area index and leaf inclination from gap fraction measurements

2.2.1. Use of a single direction

Considering the inclined point quadrat method, Warren-Wilson (1960) proposed a formulation of the variation of the contact frequency as a function of the view zenith and foliage inclination angles. Using this formulation, Warren-Wilson (1963) showed that for a view angle of 57.5° the G-function (Figure 1) can be considered as almost independent of leaf inclination ($G \cong 0.5$, $K \cong 0.9$). Using contact frequency at this particular angle (57.5°), Warren-Wilson (1963) derived leaf area index independently on the leaf inclination distribution function within an accuracy of about 7%. Bonhomme et al., (1974) applied this technique using the gap fraction measurements and found good agreement between the actual and estimated LAI values for young crops.

2.2.2. Use of multiple directions

Miller's formula

Chen and Black (1991) derived LAI from the gap fraction measured in all directions using the formula of Miller (1967) which assumes that gap fraction depends only on the view zenith angle:

$$L = 2\int_0^{\pi/2} -\ln(P_0(\theta_v))\cos\theta_v \sin\theta_v d\theta_v \tag{9}$$

Welles and Norman (1991) proposed a practical method to compute the integral of Eq. 9 from gap fraction measurements in several directions. One of the main limitations with this technique is the necessity to sample the entire directional range of gap fraction variation, which might prove difficult for larger zenith angles.

Lang graphical method

For a uniform leaf azimuth distribution and a constant leaf normal angle, Lang (1986) approximated $G(\theta_v)$ as a linear function of θ_v in the 25° - 65° range. The slope of the regression ($\partial G(\theta_v)/\partial \theta_v$) was then related to the ALIA by polynomial fitting. Using an initial estimate of LAI based on gap fraction measurements at a 55° (close to the 57.5°) zenith angle, (Lang, 1986; Welles and Norman, 1991), the slope $\partial G(\theta_v)/\partial \theta_v$ can be estimated and thus, the ALIA can be derived. Therefore, the LAI estimates can be refined, and the process is iterated several times until convergence.

The method was successfully validated with other leaf inclination distributions (Table 2) and measurements over sorghum crops. However, no comparison is shown with the initial estimates at 55° (or 57.5°). Although several zenith angles are used, the emphasis is on this particular 57.5° zenith angle. We should note that this technique could be used to compute the ALIA.

Model inversion

As seen previously, mathematical models that relate LAI and LIDF to the gap fraction exist and can be inverted from gap fraction measurements performed in several directions. A review of existing numerical techniques applied to radiative transfer model inversion is given in Kimes et al. (2000) and an inter-comparison is performed by Combal et al. (2002). This technique is appealing since it allows exploiting several directions concurrently without introducing approximations as done previously. In addition, it provides an estimate of the ALIA for a given LIDF model.

In the following, we will compare the different LAI retrieval techniques using an experimental data set. Assuming an ellipsoidal distribution, ALIA will also be computed using these techniques based on gap fraction measurements in several directions.

Comparison of LAI retrieval methods

The objective here is to evaluate the consistency of the different methods for LAI (and ALIA) estimation. We consider the canopy as a random turbid medium where the Poisson model applies, with an ellipsoidal LIDF. The discussion about the limitations associated to these assumptions will be presented separately.

In the framework of the VALERI project (Baret et al., 2003), a wide range of canopies including agricultural crops (wheat, maize, alfalfa, barley, colza, hemp, pea, sunflower, sugar beet and poppy), cultivated forests (pine and palm), and natural forests (birch, pine and spruce) were sampled using the LAI2000 instrument to measure the gap fraction in five zenith directions (7°, 23°, 38°, 53°, 68°). The sampling strategy was designed to be representative of an area 20m in diameter, referred to as an elementary sample unit (ESU). This was achieved by measuring the gap fraction at 48 different locations within the ESU. The individual gap fraction measurements were averaged over the ESU for each direction in accordance with the procedure discussed later in this paper (§3). An azimuth mask of 180° was used on the LAI2000 sensor probe and measurements were always achieved under diffuse conditions.

Four retrieval techniques to derive leaf area index and average leaf inclination angles from P_o measurements were compared:

1. The method based on gap fraction measurements at a zenith angle of 57.5°. The gap fraction was linearly interpolated between 53° and 68° since there were no gap fraction measurements measured at this specific angle.
2. The Miller's formula method as approximated by Welles and Norman (1991).
3. Gap fraction model inversion using an iterative optimisation technique (Perry et al., 1988). The Poisson model (Eq. 7) is used and the leaf angle inclination is assumed to be azimuthally isotropic with an ellipsoidal zenith angle distribution. Starting with an initial estimate of LAI (LAI provided by method 1) and ALIA (ALIA=60°), the gap fraction model is run in the forward direction to simulate the gap fraction in all five directions. The variables LAI and ALIA are then iteratively changed, using the simplex algorithm (Nelder and Mead, 1987), until a good agreement is met between the simulated and measured gap fraction values. The cost function used is the simple quadratic distance. A constraint is applied to the cost function so that the leaf area index is always within a range of 0 and 9 and ALIA is between 0° and 90°.
4. Since the optimisation process is an iterative process and is, therefore, more computationally demanding, Look-Up-Table (LUT) techniques (Knyazikhin et al., 1998; Weiss et al., 2000) could prove convenient for operational use. Furthermore, the search for LAI and ALIA is global, minimizing the probability of being trapped at a local minimum as seen with the optimisation method. A large range of random combinations of LAI (between 0 and 9) and ALIA (between 0° and 90°) values is used to build a database made of the corresponding gap fraction values simulated in the five directions considered for 5000 cases. The same Poisson model and ellipsoidal LIDF explained in the optimisation technique are used. The process then consists of selecting 25 LUT elements in the database that are closest to the measured P_o. The number of 25 cases was selected in agreement with the uncertainties associated to the gap fraction measurements. The solution is finally approximated using the median of these 25 LAI (and ALIA) values.

The LUT method was chosen as the reference for comparison with the other methods. Figure 2 demonstrated that there is a very good agreement between the LUT method and that using gap fraction observed at 57.5°. The largest discrepancies are observed for the larger LAI values for which saturation problems may occur. These discrepancies increased significantly when using Miller's formula approximated by Welles and Norman (1991). The optimisation method (OPT) provides the largest scattering compared to the LUT results, particularly for the largest LAI values. Instability of the inversion process mainly explains this difference which clearly appears when considering the retrieved ALIA values: Figure 2 shows that the ALIA derived from the OPT method is systematically higher than that derived from the LUT method. Inspection of the ALIA values derived from the Lang (1986) method shows a suspicious stability of the values.

2.3. From effective leaf are index to true LAI

2.3.1. The clumping effect

As mentioned in §2.1.1, the "true LAI" defined in the introduction can only be measured using a planimeter using all possible allometric relationships in order to reduce the sampling (Frazer et al., 1997). Generally, actual canopy foliage is not randomly distributed due to vegetation structure. Therefore, retrieval of LAI based on the Poisson model and using gap fraction measurements will provide estimates of an effective LAI, LAI^{eff}, which allows a description of the observed gap fraction assuming a random spatial distribution:

$$L^{eff} = \lambda_o L \tag{10}$$

where λ_o is the aggregation or dispersion parameter (Nilson 1971; Lemeur and Blad, 1974) or clumping index (Chen and Black, 1992). Comparing LAI derived from optical devices with the true LAI value measured with destructive sampling leads to an underestimation in the case of aggregated canopies where $\lambda_o<1.0$ and overestimation for regular foliage where $\lambda_o>1.0$ (Fassnacht et al., 1994).

The λ_o value depends on both the plant structure, *i.e.* the way the foliage is located along the plant stems and on trunks, branches or shoots for trees (small scale), and the canopy structure, *i.e.* the relative position of the plants within the canopy (large scale). In the case of large scale clumping, as it occurs in row crops, the true LAI can be estimated through indirect measurements via an appropriate sampling and averaging strategy (Lang and Yuequin, 1986, see §3). The shape and size of the leaves might also play an important role in clumping.

A detailed description of how the structure of different pine forests can affect light interception inside the canopy is given in Stenberg et al., (1994). Assuming that clumping only occurs at the shoot scale in coniferous forests, Chen and Cihlar (1995b) proposed to relate λ_o to the ratio of half the total needle area in a shoot to half the total shoot surface area. Chen and Cihlar (1995a) measured this ratio and found up to 50% difference between the effective and the actual LAI in coniferous forests. This was confirmed by several studies that found LAI underestimation by 30% to 70% (Stenberg, 1996, Nackaerts et al., 1999). However, the occurrence of clumping is not restricted to the shoot level, but may also take place at the branch and crown levels (Chen *et al.*, 1997). Moreover, studying a spruce forest, Cescatti (1997b) shows that the distribution of shoots is more regular than random. Chason et al (1991) successfully inverted the negative binomial model on LAI2000 measurements to retrieve the “true LAI” of an oak-hickory forest, showing a 45% difference between actual and effective LAI.

Nilson (1971) suggests relating λ_o to the size and the distance between vegetative elements and Andrieu and Sinoquet (1993), as well as Kucharik et al. (1998; 1997), observe that it also depends on the viewing (or incident) direction. In addition, they compare the angular variation of this parameter for a homogeneous canopy (LAI only varies as a function of the height of the canopy) and a row crop in case of artificial canopies, for which all parameters and variables are well known. Results show that for row crops, the clumping parameter is highly dependent on the direction of observation, which makes λ_o estimation difficult in the case of actual canopies. Additionally, Andrieu and Sinoquet (1993) show that for row crops it is more important to take into account the spatial variation of the leaf area density than the leaf orientation or dispersion. Results from Baret et al. (1993) on sugar beets and young wheat confirm that the azimuthal variation of the gap fraction is only significant near the row direction.

The LAI estimate provided by these instruments is an effective leaf area index. By measuring the gap size distribution along transects, Chen and Cihlar (1995a) define a gap-size accumulation function $F(d)$ that represents the transect fraction which corresponds to gaps larger than d. $F(0)$ is therefore the fraction of the transect occupied by gaps. For non-regular canopies, the clumping parameter is expressed as the ratio of the logarithm of total measured gap fraction $\ln(F_m(0))$ to the logarithm of the gap fraction $\ln(F(0))$ of an equivalent canopy with random foliage distribution.

2.3.2. Distinction between green and non green elements

Neumann et al. (1989) suggested an interesting method to estimate the clumping parameter from the Markov model, as described by Nilson (1971). It is based on a dedicated processing of hemispherical photographs focusing on the conditional probability of gaps in two directions close together. Note that this processing has some similarities with that proposed by Chen and Cihlar (1995a), which exploits the gap size distribution.

As noted in the introduction, the investigations requiring LAI measurements are generally linked to the description of canopy functioning. Therefore, the green photosynthetic parts should be specifically targeted. When estimating leaf area index from gap fraction measurements, it is not possible to directly distinguish between green and non-green elements such as branches, stems, trunks, flowers, fruits, senescent leaves or lichen. Both Whitford et al. (1995) and Chen et al. (1997) mention that an important source of error in indirect measurements comes from woody areas (trunks and branches) that may be taken into account as green vegetative elements. Therefore, alternative terms have been proposed in the literature such as “vegetation area index” (Fassnacht et al., 1994), “plant area index” (Neumann et al., 1989), or “foliage area index” (Welles and Norman, 1991). For particular canopies such as forests or crops in the senescent period, it could prove particularly important to differentiate the green from non-green elements. Chen (1996) introduces the a parameter which is expressed as the ratio of woody area index to plant area index. Therefore, considering non-green elements in the canopy, a new expression of the effective leaf area index can be derived:

$$L^{eff} = \frac{l_o}{1-a} L \tag{11}$$

Chen (1996) evaluates a *from* intensive destructive measurements. Barclay et al. (2000) also proposed to correct LAI^{eff} using a "bole area index" directly measured using a map of the stand (position of the stems, diameter, height, etc.). Both of these methods are quite tedious and one solution could be a classification method applied on digital imagery. Using the MVI instrument, Kucharik et al. (1998) used a clustering algorithm called BIRCH (Balanced Iterative Reducing and Clustering using Hierarchies). BIRCH is based on the K-means clustering algorithm, that allows the two bands to be weighted by different factors and, therefore, to identify sunlit and shaded foliage, sunlit and shaded branch area, clouds, and blue sky.

3. SAMPLING STRATEGIES

Spatial sampling is a key issue when performing ground measurements that need to be representative of the whole canopy. Very little literature is dedicated to the sampling strategy although this is critical for reaching a targeted accuracy. We will review in the following the few studies reported in the literature and present some additional results based on intensive LAI2000 measurements campaigns that took place within the VALERI project (Baret et al., 2003). We will review in the following the different elements that define a sampling strategy: the number of individual readings and their location, as well as the averaging process.

3.1. Number of measurements and location

Three types of spatial sampling strategy are distinguished depending on the devices used, the canopy architecture and the size of the area to be described.

- Transects between 50m to a few hundred meters long are used for devices measuring the direct sun radiation such as ACCUPAR, TRAC or DEMON (Chen, 1996; Lang et al., 1991; Welles, 1990). The same could be also done with, LAI2000 and hemispherical photographs. For example, Leblanc et al. (2002) used 70 m long transects over boreal and temperate forests, with measurements every 10m.
- Specific experimental designs based on regular grid sampling are proposed by (Law et al., 2001; Nackaerts et al., 2000) for the LAI2000 instrument; but that could also be applied to hemispherical photographs. Alternative methods consist in random locations within plots of few hundred km² in size as proposed by (Rich et al., 1993; Wang and Miller, 1987; Whitford et al., 1995) for large area sampling. Chen et al. (1997) also proposed to

acquire hemispherical photographs in a crisscross array at 10m intervals along two 40m long transects placed at right angles and crossing in the middle. Neuman et al. (1989) use a random distribution of nine measurements within a 15×15m² elementary sampling unit. Baret et al. (2003) proposed to characterise an elementary sampling unit of few tens of metres by performing 12 replicates either organized in a cross or in squares.

- Adapting the sampling strategy to the local canopy pattern: Conversely to the two first strategies, where measurements were located independently of local canopy patterns, Lopez-Serrano et al. (2000) proposed an optimised sampling strategy for forest by standardizing the distance and orientation of the LAI2000 measurements from a tree. However, the results of this method show no actual differences from the strategy based on transects except that its measurements are less tedious. Note that in the case of the description of individual trees, dedicated methods have been proposed either by a specific extensive sampling (Lang et al. 1991) or by taking into account the path length associated to each measurement location and direction. Note that in the case of row crops, it is wise to design a sampling strategy that accounts for the main architectural feature of the canopy. This is generally achieved by replicating measurements at a range of distances between rows.

Note that in addition to the above criteria used to design the sampling strategy, the objective should be clearly defined in terms of the extent of the spatial domain to be represented. In the case of large areas, local measurements could be extended to the whole area thanks to remote sensing measurements (Baret et al., 2003; Cohen et al., 2003;Chen, 1999; Tian et al., 2002) or using geostatistical techniques such as kriging (Goovaerts, 1997). In the following discussion, we will focus on spatial domains corresponding to few tens of metres within which only one canopy type is represented.

To illustrate the influence of the required number n of gap fraction measurements, we used the first VALERI sites considered (Baret et al., 2003) for which intensive sampling was achieved. For wheat crops (Alpilles –France- and Fundulea –Romania- sites), 48 individual measurements were taken to characterize a typical 20m diameter elementary sampling unit (ESU). In this case, 63 ESUs were sampled for wheat crops. A simple statistical test shows that the measurements within an ESU were not significantly correlated at these very short distances. For a pine forest (Nezer site), 30 individual measurements were performed with the same instrument randomly within each 80m diameter ESU. 23 ESUs were considered for these pine canopies. LAI was estimated using the LUT method with the 57.5° direction as proposed previously (section 2.2.1). For wheat crops, we randomly selected 12 (then 24) individual measurements over the 48 individual acquisitions within an ESU. For the pine canopies we randomly selected 10 measurements (then 20) over the 30 individual acquisitions within an ESU. This process was repeated 50 times over each ESU. The corresponding *RMSE* value between the LAI estimated from all acquisitions and the LAI estimated from only part of the individual measurements was computed over the 50 replicates. Results (Figure 3) show that the distribution of the *RMSE* values over the ensemble of ESUs is narrow and centred on relatively low values. This indicates that the number of individual measurements could be reduced to 10 per ESU for both wheat and pine canopies. This is in good agreement with the methodology described earlier where between 5 to 15 individual measurements were taken. More recently Leblanc et al. (2002) proposed to use only four hemispherical photographs to get a good sampling of temperate and boreal forests.

3.2. Spatial averaging for representative leaf area index estimation

There are two methodologies that derive LAI from individual gap fraction measurements; these methods might not be equivalent due to the non-linearity between LAI and P_0, and spatial heterogeneity. The methodologies are:

1. Averaging individual gap fraction measurements and then deriving LAI of the stand
2. Averaging LAI values derived from individual gap fraction measurements

An additional and intermediate way (3) was also investigated, that consists in averaging the gap fraction over the group of 4 individual measurements, computing the corresponding LAI, and then averaging the LAI values over the 12 groups. This would obtain measurements, which were more locally representative. This last approach is close to that described in Lang et al. (1991) who used the Demon device and recommend to first average the gap fraction along a line segment at least ten times the mean width of a leaf, to compute the corresponding *LAI*, and finally, to average the LAI obtained over a number of such transects.

In the case of an ideally homogeneous canopy, strategies (1) (2) and (3) should be theoretically equivalent. Conversely, in the case of a heterogeneous canopy, strategies (1) (2) and (3) should give different results due to the non-linearity of the relationship between gap fraction and LAI. Van Gardingen et al., (1999) investigated the ratio between the two above described LAI estimates. They suggested relating this ratio to the clumping index although it seemed to be more linked to a scaling issue within heterogeneous canopies rather than a pure clumping index as defined by Chen and Black (1992).

To further compare the two spatial averaging strategies, measurements performed on an agricultural site (Alpilles) sampled in 2001, will be used. 51 ESUs were sampled. Each ESU had a 20m diameter area. A group of four individual LAI2000 measurements separated within around 1 meter transect across the rows were performed to take into account this architectural pattern. The groups of four individual replicates were lying along the arms of a 20m cross, each group being separated by 4m. This makes 12 groups of 4 individual measurements, i.e. 48 measurements per ESU. Figure 4 shows the comparison between the two strategies using a LUT inversion technique, *i.e.*, (1) deriving LAI for each individual below canopy measurement and then averaging the 48 corresponding estimated LAI values, (2) averaging the gap fraction over the 48 measurements and then deriving the LAI. An additional and intermediate way (3) was also investigated; it consisted of averaging the gap fraction over the group of four individual measurements, computing the corresponding LAI, and then averaging the LAI values over the 12 groups. This last approach allows for more locally representative measurements and is similar to that described in Lang et al. (1991). Lang et al. (1991) used the Demon device and recommended averaging the gap fraction along a line segment at least ten times the mean width of a leaf, to compute the corresponding LAI, and finally, to average the LAI obtained over a number of such transects.

When using the directional variation of P_0, the directional measurements should represent the same canopy. Therefore, the averaging process might depend on the number of directions corresponding to the LAI2000 rings used, to derive the leaf area index. These were concurrently investigated.

Results (Figure 4) show that when measuring gap fraction in a single direction there is little difference between strategies (1) (2) and (3), although it is theoretically better to use strategy (2) (Lang and Yueqin, 1986). When simultaneously exploiting several directions, the differences tend to increase with the range of directions used. However, methods (2) and (3) appear more similar due to the directional P_0 measurements used to retrieve LAI being more representative of the canopy. Note however that our case study corresponds to agricultural canopies relatively homogeneous over a 20m diameter ESU: the maximum RMSE value between the 3 methods is relatively small and lower than 0.1.

In conclusion, it should be stated that method (1) should be used when considering single direction measurements. Note however that the LAI 2000 device inherently averages over a range of azimuthal directions, depending on the mask cap used on the lens. In the case of single zenithal direction used and heterogeneous canopies, small aperture caps should be preferred. Conversely, when using several directions concurrently or when considering the gap size distribution (Lacaze and Tabarant, 1998), methods (2) or (3) should be used. In this case, a larger aperture cap on the LAI2000 lens would be recommended to allow a better canopy sampling.

3.3. Required number of directions to derive leaf area index

The impact of the number of directions used to derive leaf area index was studied over an ensemble of VALERI sites sampled with the LAI2000 in 2000 and 2001. These sites correspond to a range of canopies: 3 agricultural (Romilly, Fundulea, Alpilles), 2 coniferous forests (Järvselja, Nezer) and a palm tree plantation (Aek Loba). 30 to 50 individual measurements were performed at each site to characterize the 303 elementary sampling units considered. The spatial averaging process was achieved using method (2), i.e. the LAI was derived from the average of individual gap fractions. The gap fraction at 57.5° which allows direct LAI estimation (§2.2.1) was computed as a weighed average between the

4^{th} and 5^{th} rings. This was compared to LAI values derived from gap fractions measured in rings 2 to 5. The first ring centred at 7° was not used because it always provided poor results due to the associated restricted sampling. Figure 5 shows good agreement between the two estimations. However, the agreement is better for forest canopies (RMSE = 0.15) than for agricultural areas (RMSE = 0.57). From these results, it seems quite reasonable to propose the derivation of the LAI from the gap fraction measurements at 57.5° because it provides very simple and robust estimates. These results also corroborate those of Leblanc et al. (2001). Furthermore, it allows the application of the best averaging process, i.e. method (1) that should be the most independent of the level of spatial heterogeneity of the canopy. However, using one single direction does not allow the derivation of leaf angle distribution, which is an important feature in the vegetation radiation regime.

4. CONCLUSION

This review into methods used to estimate LAI from gap fraction measurements is addressing several issues. The first one is associated to the retrieval technique used to 'invert' the gap fraction model in the case of multidirectional measurements. LUT techniques appear appealing because it allows adjusting the leaf angle distribution, which could be an important canopy characteristic, used within radiation transfer processes. However, the success of the inversion will mainly rely on the underlying assumptions and also on the quality of the measurements and their associated representativity.

Considering the assumptions used in the gap fraction models currently used, the main problems to face are the clumped nature of leaves and the mixture of green and non-green vegetation elements. With respect to clumpiness, theoretical treatments exist and some of them have already been exploited. They allow an account of this feature using prior knowledge of the clumping parameter. However, the limitation of the proposed correction factors is that they are not universally applicable (Deblonde *et al.,* 1994, Stenberg, 1996). Nilson (1999) proposes to use a detailed canopy architecture model to derive the actual leaf area index over forest canopies. However, this requires independent knowledge of some canopy characteristics such as tree density, crown size that might difficult to measure with sufficient accuracy. A very interesting alternative is to focus on the gap size distribution as proposed by Chen and Cihlar (1995a). Although there were some limitations in the measurement a few years ago, the availability of high resolution hemispherical digital cameras at low cost requires an urgent revisit to this efficient concept, as already done by Leblanc et al. (2002). This could be done in conjunction with advanced representation of canopy architecture as proposed by Nackaerts *et al.* (2000) using a fractal approach. However more theoretical insight is required to investigate the validity of current theories, with an emphasis on the directional dependence of clumping as well as clumping scale (needle/leaf, shoot, plants …). The 3D computer generated canopies will provide a very convenient tool for such investigations as proposed by Cescatti, (1997a) and Rochdi et al., (2003).

Considering the problem of the distinction between green and non-green vegetation elements, the current methods are mainly based on locally calibrated values of the α ratio between the green and non-green area indices. Similarly to the clumping issue, the α ratio could vary widely depending on canopies and also on direction. The use of devices that allow separating between green and non-green vegetation elements such as digital cameras imaging in several wavebands.

Considering the sampling strategy, this review shows that the question is quite complex and should be addressed in further studies. Although our results tend to prove that very few measurements are required for wheat and pine canopies, particular attention should be paid to the number of measurements required to best represent a given canopy. This is a critical issue for discontinuous canopies such as row crops or bushes as well as for measuring the leaf area index of a single tree. The number of gap fraction measurement directions required to derive leaf area index is a less critical issue, since one single direction (57.5°) appears to be enough. However, if additional information on the leaf inclination distribution is to be derived using an inversion procedure, more than two directions are required. The use of hemispherical images and enhanced canopy modelling will certainly provide efficient and mandatory tools to advance the problem of canopy architecture measurement from non-destructive measurements.

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Table 1. Notation.

ALIA	Average leaf inclination angle
ESU	Elementary sampling unit
$G(\theta_v, \varphi_v)$	Mean projection of unit foliage area
$g(\theta_l, \varphi_l)$	Distribution function of foliage inclination and orientation
K	Extinction coefficient
$l(h)$	Leaf area density at level h in the canopy
LAI, L	Leaf area index
LAI^{eff}, L^{eff}	Effective leaf area index
LIDF	Leaf inclination distribution function
P_0	Gap fraction
$N(H, \theta_v, \varphi_v)$	Mean number of contacts in a given direction at height H
α	Ratio of woody area index to plant area index
λ_o	Clumping or aggregation parameter
θ_l, φ_l	Zenith and azimuth angles of the leaf normal
θ_v, φ_v	Direction for which the incident beam (or the probe) penetrates inside the canopy
ψ	Phase angle between directions θ_l, φ_l and θ_v, φ_v

Table 2. Main expressions of the leaf inclination distribution function. $g(\theta_l)$ is the distribution function of foliage inclination (assuming a uniform distribution function of the leaf azimuth angle), ALIA is the Average Leaf Inclination Angle θ_l , μ and ν are the beta distribution parameters.

Canopy Type	$g(\theta_l)$	ALIA, $\overline{\theta_l}$, (°)	$<\theta_l^2>$	μ	ν
Planophile	$2(1+\cos 2\theta_l)/\pi$	26.8	1058.6	2.770	1.172
Erectophile	$2(1-\cos 2\theta_l)/\pi$	63.2	4341.4	1.172	2.770
Plagiophile	$2(1-\cos 4\theta_l)/\pi$	45.0	2289.6	3.326	3.326
Extremophile	$2(1+\cos 4\theta_l)/\pi$	45.0	3110.3	0.433	0.433
Uniform	$2/\pi$	45.0	2700.0	1.000	1.000
Spherical	$\sin\theta_l$	57.3	3747.6	1.101	1.930

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Figure 1. Variation of the G-Function (mean projection of unit foliage area) with the average leaf inclination angle q_l and view zenith angle q_v under the assumption that the distribution of leaf normals is uniform in azimuth and at a constant zenith angle q_l .

Figure 2. Leaf area index (LAI) and average leaf inclination angle (ALIA) estimation from LAI2000 gap fraction measurements. Comparison between three inversion techniques: LAI2000 computation, Optimisation (OPT), Look-Up-Table (LUT), and LAI estimated from gap fraction at 57.5° (P_o(57.5°)). RMSE stands for the root mean square error. Crops are represented by solid triangles and forest by open symbols.

Figure 3. Histograms of RMSE between LAI estimated from all the LAI2000 acquisitions (Look-Up-Table method), and LAI estimated from only part of the acquisitions (50 random samples). Measurements were performed over a 20mx20m area for crops (Alpilles and Fundulea sites) and 80mx80m area for pine forest (Nezer site).

Figure 4. Comparison between the three gap fraction spatial averaging methods for LAI estimation using Look-Up-Table method, as a function of the number n of LAI2000 rings used for the inversion (VALERI, Alpilles site, March 2001, LAI between 0 and 4). (1) Deriving LAI from each individual gap fraction (P_0) measurement in the n rings, and averaging LAI (48 LAI values), (2) deriving LAI from the average gap fraction value from the 48 P_0 measurements in the *n* rings, (3) deriving LAI for each local gap fraction measurement (average over the 12 LAI values computed from the average gap fraction computed for the 4 local replicates).

Figure 5. Comparison between LAI estimated from one direction and LAI estimated from 4 directions for the VALERI 2000 and 2001 sites. Forests are represented by open symbols, agricultural areas by solid triangles.

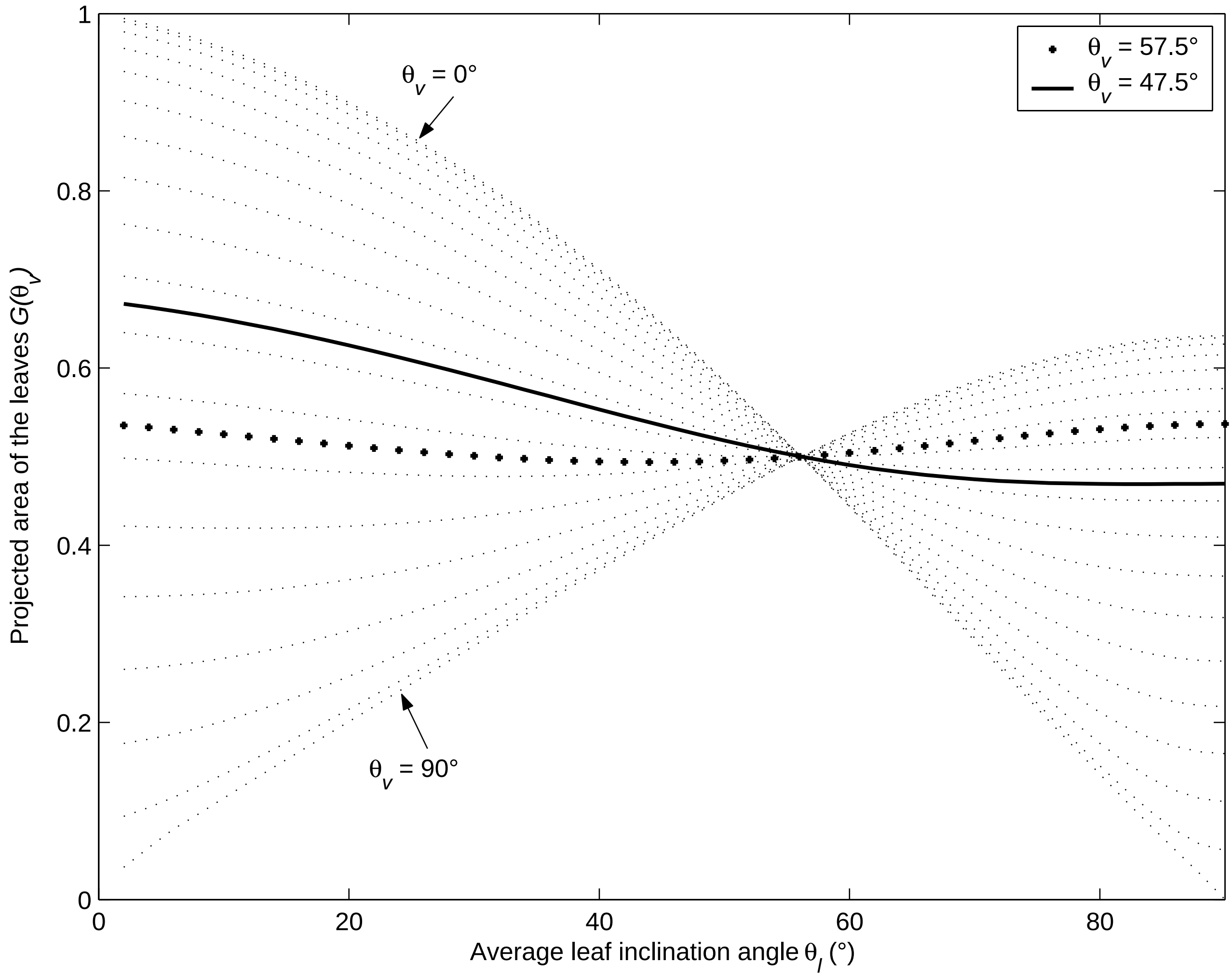
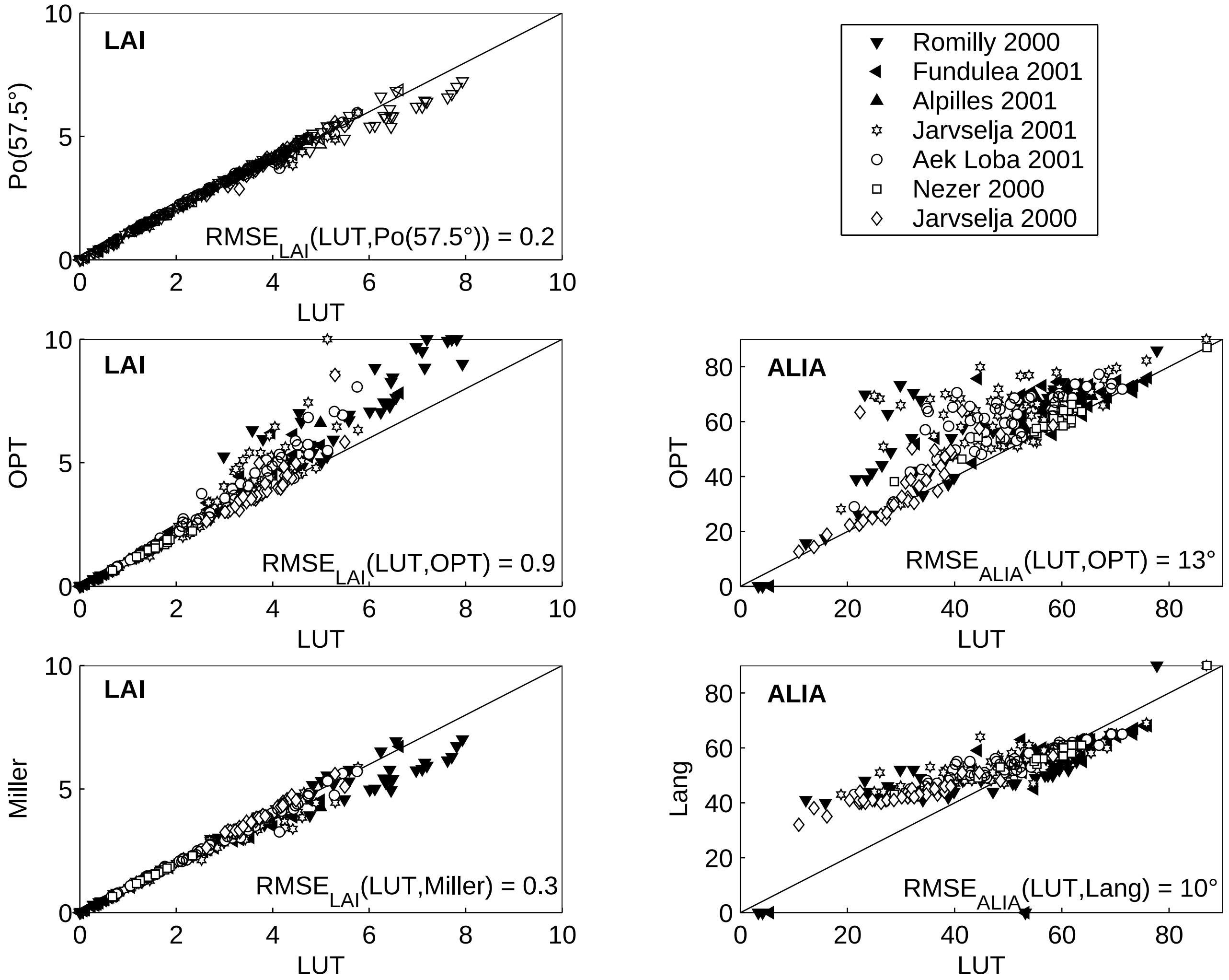


Figure 1. Variation of the G-Function (mean projection of unit foliage area) with the average leaf inclination angle θ_l and view zenith angle θ_v under the assumption that the distribution of leaf normals is uniform in azimuth and at a constant zenith angle θ_l .



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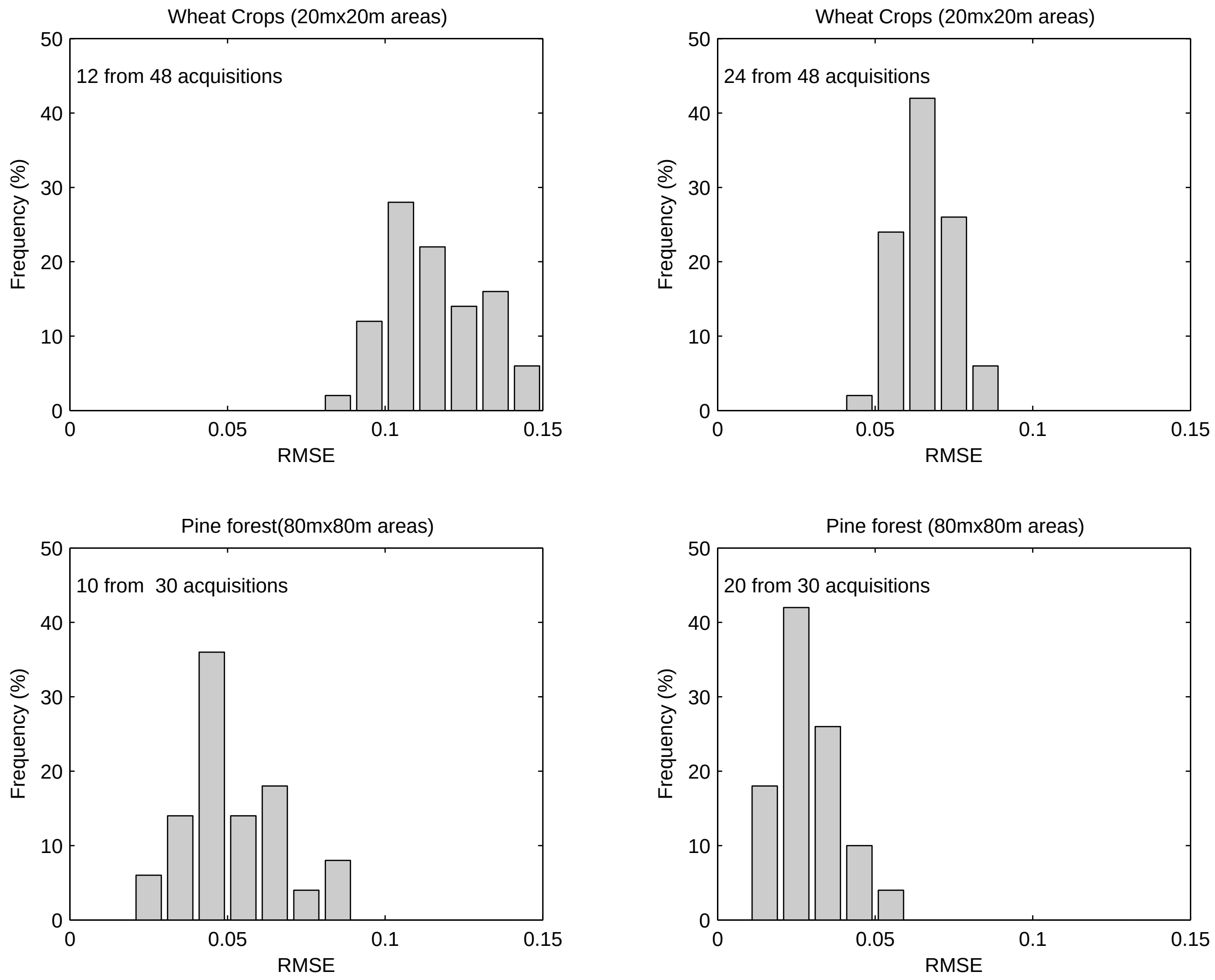

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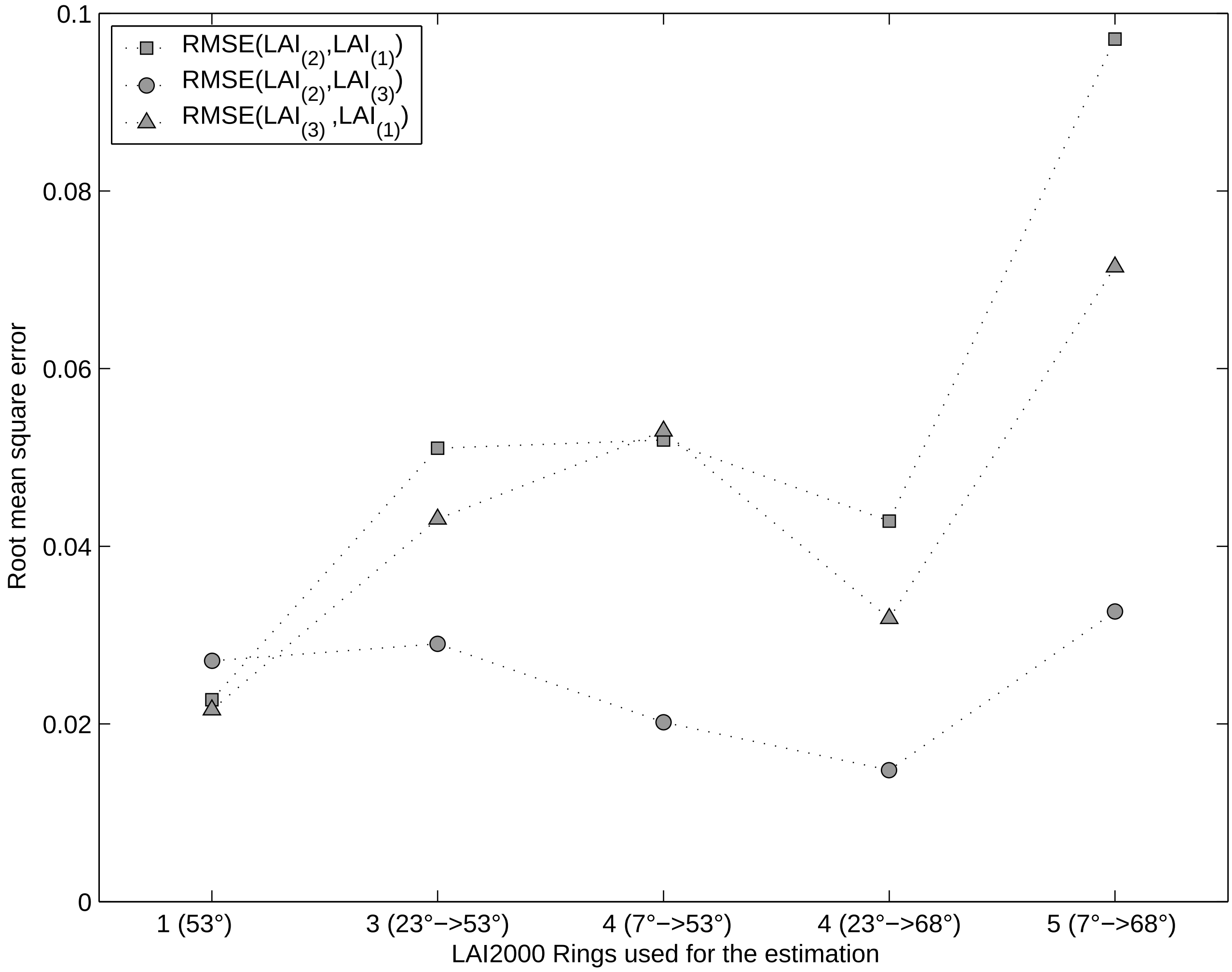

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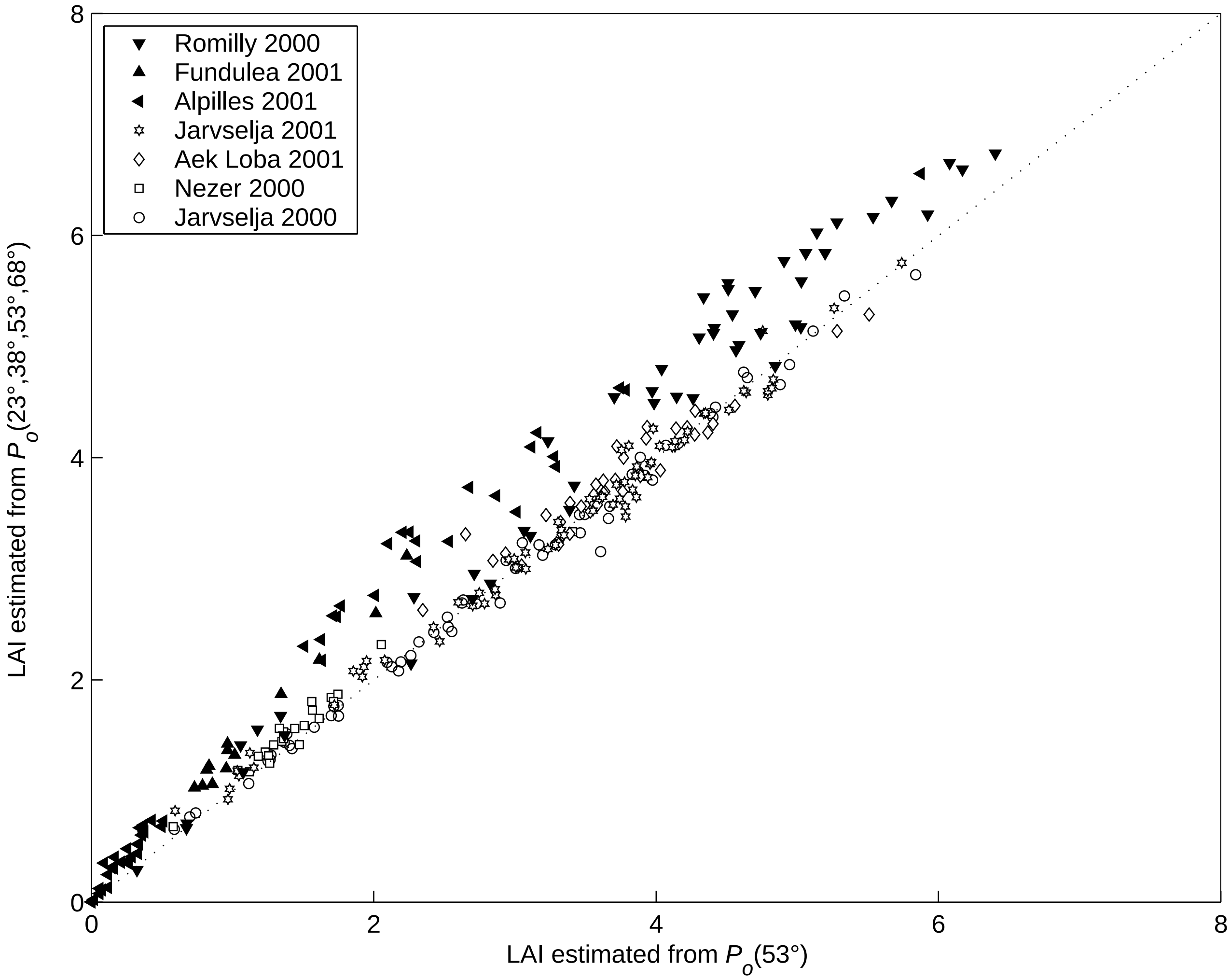

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