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Ground-based measurements of leaf area index: a review of methods, instruments and current controversies

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Abstract

Leaf area index (*LAI*) is the total one-sided area of leaf tissue per unit ground surface area. It is a key parameter in ecophysiology, especially for scaling up the gas exchange from leaf to canopy level. It characterizes the canopy–atmosphere interface, where most of the energy fluxes exchange. It is also one of the most difficult to quantify properly, owing to large spatial and temporal variability. Many methods have been developed to quantify *LAI* from the ground and some of them are also suitable for describing other structural parameters of the canopy. This paper reviews the direct and indirect methods, the required instruments, their advantages, disadvantages and accuracy of the results. Analysis of the literature shows that most cross-validations between direct and indirect methods have pointed to a significant underestimation of *LAI* with the latter techniques, especially in forest stands. The two main causes for the discrepancy, clumping and contribution of stem and branches, are discussed and some recent theoretical or technical solutions are presented as potential improvements to reduce bias or discrepancies. The accuracy, sampling strategy and spatial validity of the *LAI* measurements have to be assessed for quality assurance of both the measurement and the modelling purposes of all the *LAI*-dependent ecophysiological and biophysical processes of canopies.

Key words: Clumping, error, leaf area index, plant area index, sampling.

Introduction

Leaf Area Index (*LAI*) was defined by Watson (1947) as the total one-sided area of leaf tissue per unit ground surface area. According to this definition, *LAI* is a dimensionless quantity characterizing the canopy of an ecosystem. Leaf area index drives both the within- and the below-canopy microclimate, determines and controls canopy water interception, radiation extinction, water and carbon gas exchange and is, therefore, a key component of biogeochemical cycles in ecosystems. Any change in canopy leaf area index (by frost, storm, defoliation, drought, management practice) is accompanied by modifications in stand productivity. Process-based ecosystem simulations are then often required to produce quantitative analyses of productivity and *LAI* is a key input parameter to such models. Ecophysiologists, but also managers (farmers and foresters), ecologists, site and global modellers, request information about canopy leaf area index. Unfortunately, this interface between ecosystem and atmosphere is very difficult to quantify, due to its spatial (horizontal and vertical) and temporal variability: annual cycles and interannual variability interact with the stand or crop structure, stratification and heterogeneity.

Since the reviews of Norman and Campbell (1989) and Welles (1990), many comparisons between the direct and indirect methods of *LAI* measurement have been published for crops (Brenner *et al.*, 1995; Levy and Jarvis, 1999) and forest stands (Chason *et al.*, 1991; Smith *et al.*, 1991; Fassnacht *et al.*, 1994; Dufrêne and Bréda, 1995; Comeau *et al.*, 1998; Barclay and Trofymow, 2000; Küßner and Mosandl, 2000). Although no completely new equipment has been explicitly developed for *LAI* measurements since 1990, new topics including error analysis, cross-calibration, sampling strategy, spatial validation or scaling are emerging from the recent literature.

The objective of the present paper is to review all available ground-based methods for leaf area index measurement at site and stand/crop scales. Discussion of remotely sensed vegetation indices (either from satellite or air-borne high-resolution imagery) has been deliberately

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omitted though they have novel potential. From personal experience in forest ecology, remotely sensed vegetation indices at present need a site- and stand-specific calibration against ground-based measurements of *LAI* and still do not yield suitable results for complex canopies such as forests with a high *LAI*. Chen *et al*. (2002) reached a similar conclusion recently for *LAI* mapping in Canada. It is necessary to rely first on ground-based *LAI* estimates if remotely sensed vegetation indices need cross-calibration.

Materials and methods

Direct methods

Direct or semi-direct methods involve a measurement of leaf area, using either a leaf area meter or a specific relationship of dimension to area via a shape coefficient. In coniferous species, projected leaf area differs from the developed one by a coefficient depending on a needle cross-sectional area (Grace, 1987; Barclay, 1998; Sellin, 2000). Leaf area is measured on a sub-sample of leaves and related to dry mass (e.g. via specific leaf area, *SLA*, cm^2 g^{-1}). Finally, the total dry mass of leaves collected within a known ground-surface area is converted into *LAI* by multiplying by the *SLA*. As the direct methods only relate to foliage, they are the only ones giving real access to leaf area index. They allow separate computation of the shape, size and number of leaves. Direct methods provide the reference for the calibration or evaluation of indirect methods. It is crucial to sample leaves correctly for establishing leaf area to dry mass ratio, as it changes among species and among sites for a given species. Figure 1 shows some averaged values of *LAI* estimated by direct measurements in forest stands. Direct methods include harvesting, allometry and litter collection.

Harvesting the vegetation and measuring the area of all the leaves within a delimited area is the first method, widely used for crops and pastures. This method is well adapted for vegetation of small structure, but is destructive. Such an exhaustive approach cannot be applied to large areas or to large trees, but it is suitable for measuring *LAI* in the space of a gas exchange chamber.

Foresters have developed a less destructive method that relates foliage area to the diameter of the sapwood area at breast height or at crown base (Grier and Waring, 1974; Albrekston, 1984; Makela *et al*., 1995). The leaf area per unit sapwood area varies from 0.15–0.75 m^2 cm^{-2} in conifers (Waring *et al*., 1982). It has been suggested that the product of sapwood area and sapwood permeability should improve the relationship with leaf area (Whitehead *et al*., 1984; Shelbrune *et al*., 1993). The underlying hypothesis is that leaf area is

in balance with conducting tissues, hence such allometric relationships are site and species dependent, and, in some cases, also year dependent. Any changes in the leaf versus sapwood area ratios due to management, health, fertility (Brix and Mitchell, 1983) or ageing are not reflected in a single allometric relationship. For broad-leaved species, most of the diffuse porous species exhibit dispersed sapwood and, in ring porous species like oaks, the efficiently conducting sapwood is limited to the most recent rings (Rogers and Hinckley, 1979). Because of the difficulties of measuring the conducting area, the sapwood area should be replaced by more readily measured variables, such as diameter at breast height (Vertessy *et al*., 1995). Finally, if the establishment of allometric relationships with leaf area is conducted in individual trees by taking into account the height of branches, the vertical distribution of *LAI* may be estimated (Bidlake and Black, 1989; Maguire and Bennett, 1996). According to these authors, estimating allometric relationships through destructive sampling is a reliable method of deriving *LAI* for a given experimental site, but remains year-dependent. Hence such an approach cannot be used to describe a time-course of *LAI* recovery after any change in canopy opening.

In deciduous stands, a non-destructive method consists of collecting leaves in traps distributed below the canopy during leaf fall. Litter collection has been widely used in forest ecology. Litter has to be collected in a number of traps with a known collecting area every second week at least to avoid losses and decomposition. Collected litter is dried (at 60–80 °C for 48 h) and weighed to compute the dry mass of litter as g m^{-2}. Leaf dry mass at each collection date is converted into leaf area by multiplying the collected biomass by the specific leaf area (*SLA*, expressed in m^2 g^{-1}). Finally, the leaf area index is the accumulated leaf area over the period of leaf fall (Fig. 2). The estimating of specific leaf area is the most critical point in this procedure. It varies with species (Chason *et al*., 1991; Niinemets and Kull, 1994; Fig. 3), site fertility (Vanseveren and Herbauts, 1977; Jurick, 1986; Burton *et al*., 1991; Fig. 4), date and year, duration of remaining in the traps, weather and even within stands (Bouriaud *et al*., 2003). Sorting leaves by species for weighing and establishing specific area ratio is of importance: litter collection is the only method giving access to the contribution of each species to total leaf area index (Fig. 5). Once again, this method is a reference one and is suitable for deciduous species: it can give a decrease of *LAI* during leaf fall (Fig. 2) and the contribution of each species to total leaf area index (Fig. 5).

First proposed by Guittet (J Guittet, personal communication), the needle technique is derived from the inclined point quadrat method (Warren Wilson, 1959, 1960, 1963). It is an alternative for sampling litter in deciduous stands without traps. A fine needle of 1 mm in diameter is plunged vertically into the litter lying on the soil, as soon
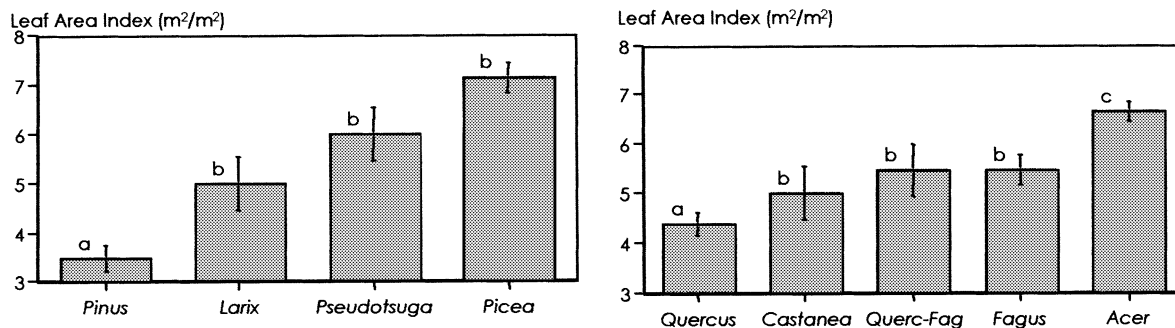

Fig. 1. Averaged *LAI* estimated from direct measurements for stands of coniferous species (by allometry) and broad-leaved species (by litter collection or allometry). Different letters indicate significant differences among species and vertical bars are 2× standard error (from Bréda *et al*., 2002).
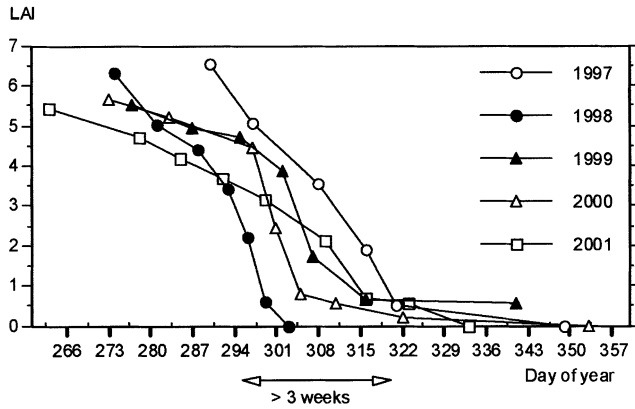
Fig. 2. Time-course of leaf area index measured by weekly litter collections during leaf fall. The starting- and end-dates of *LAI* decrease varied by 3–4 weeks between the five years studied (Bréda, unpublished data).

Fig. 3. Specific leaf area of 200 leaves including petiole and midrib collected twice during leaf fall for different broad-leaved species. Bars are 2× standard deviation. Leaf area of fresh litter was measured with an area meter (LI-3000 and LI-3050 A, Li-Cor, Lincoln, USA) and dry mass measured after 48 h drying at 105 °C (Bréda, unpublished data).

as all the leaves have fallen to avoid any decomposition of the leaves. With a vertical probe and horizontal leaves, the number of leaves collected on the needle corresponds to the contact number and equals the leaf area index. This method needs an intensive sampling (from 100 to 300 points) to quantify an average contact number and *LAI* properly (Nizinski and Saugier, 1988; Dufrêne and Bréda, 1995). The method is well suited for oak and beech forests with their large leaves and is easiest to apply in sites where litter is completely decomposed every year to avoid mixing with litter from previous years. Recently, this line-intercept method was adapted to an old Douglas-fir canopy in a spectacular way (Thomas and Winner, 2000): a vertical line (one edge of a fibreglass measuring tape, <0.10 mm thickness) was lowered from a crane from above the canopy and each intercept point was checked.

Indirect methods

Indirect methods infer leaf area index from measurements of the transmission of radiation through the canopy, making use of the radiative transfer theory (Anderson, 1971; Ross, 1981). These methods are non-destructive and are based on a statistical and probabilistic approach to foliar element (or its complement, gap fraction) distribution and arrangement in the canopy (Jones, 1992). *LAI* is calculated by inversion of the exponential expression of the gap fraction:

$$P(\theta) = e^{-\mathrm{G}(\theta,\alpha)LAI/\cos(\theta)} \qquad (1)$$

where θ is the zenith angle of view, α is the leaf angle, $P(\theta)$ is the gap fraction, $G(\theta, \alpha)$ is named the G-function and corresponds to the fraction of foliage projected on the plane normal to the zenith direction. $G(\theta, \alpha)$ depends on leaf-angle distribution α. The latter is generally not known, and the *LAI* calculation requires gap fraction measurements for a range of θ angles of view. Another alternative is to work at an angle of elevation of about 32°, which is quite insensitive to distribution of leaf inclination (Warren Wilson, 1963; Jones, 1992).

Radiation measurement and 'gap fraction'-based methods must be distinguished. The radiation measurement method uses the turbid medium analogy, which makes the assumptions that (1) leaves are randomly distributed within the canopy, and (2) individual leaf size is small when compared with the canopy. With these assumptions, gap fraction is equivalent to transmittance.
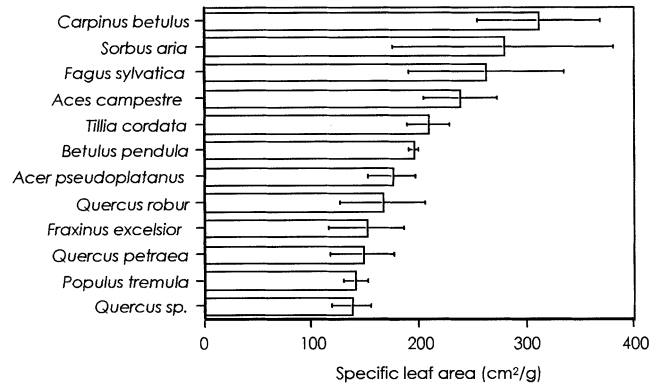
The gap fraction-based methods are dependent on leaf-angle distribution (Campbell, 1986). By inverting equation (1), the expression for *LAI* is:

$$LAI = \ln(P(\theta))\cos(\theta)/G(\theta) \qquad (2)$$

as the G-function here is independent of the leaf-angle distribution, α. The 'gap fraction'-based methods (canopy analyser systems and hemispherical images) use several ways to solve this equation as described in theory papers (Miller, 1967; Nilson, 1971; Norman and Jarvis, 1974; Ross, 1981; Norman and Welles, 1983; Lang, 1986, 1987; Norman and Campbell, 1989; Bréda *et al.*, 2002).

In fact, the indirect methods do not measure leaf area index, as all canopy elements intercepting radiation are included. Therefore, the terms of plant area index (*PAI*) or surface area index (*SAI*) are preferred if no correction to remove branches and stems is made.

Radiation measurement method: Monsi and Saeki (1953) expanded the Beer–Lambert extinction law to plant canopies. The law of Beer–Lambert expresses the attenuation of the radiation in a homogenous turbid medium. In such a medium, the flux is absorbed proportion-ately to the optical distance. The method of *LAI* evaluation by the inversion of the Beer–Lambert equation requires the measurement of both incident (I_o) and below-canopy radiation (I). Following Monsi and Saeki (1953) and with a random distribution of leaves within the canopy:

$$I = I_o e^{(-k \times LAI)} \text{ hence } LAI = -1/k \ln(I/I_o) \qquad (3)$$

where I_o is the incident radiation, I is the radiation transmitted below-canopy, k is the extinction coefficient and *LAI* is the leaf area index. From equation (2), the expression for k is:

$$k(\theta, \alpha) = G(\theta, \alpha)/\cos(\theta) \qquad (4)$$

i.e. k is a function of leaf angle distribution, α, and leaf-azimuth angle θ (Jones, 1992). The incident radiation can be measured above the canopy or in a nearby open area in the case of tall stands. Beer–Lambert's equation is inverted to compute k, based on an independent direct measurement of *LAI* (by allometry or litter fall) and on the measured transmittance (Vose and Swank, 1990; Smith *et al.*, 1991; Burton *et al.*, 1991). Then, seasonal transmittance and k
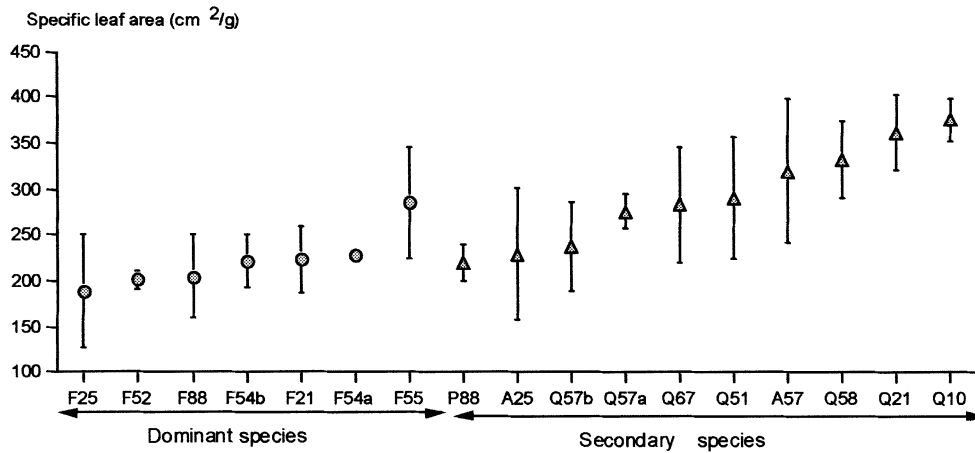
Specific leaf area (cm ^{2}/g)

Fig. 4. Variability of specific leaf area of beech litter collected from 18 French Level II-plots in the Intensive Monitoring of Forest Ecosystems network in Europe (RENECOFOR). For sites named 'F', *Fagus sylvatica* was the dominant species. The dominant species in the other plots were *Picea abies* (P), *Abies alba* (A), *Quercus* sp. (Q), respectively. In these stands, beech was a secondary species, not necessarily in the upper part of the canopy. Specific leaf area was determined as described in Fig. 3. Vertical bars are 2× standard deviation (Bréda, unpublished data).
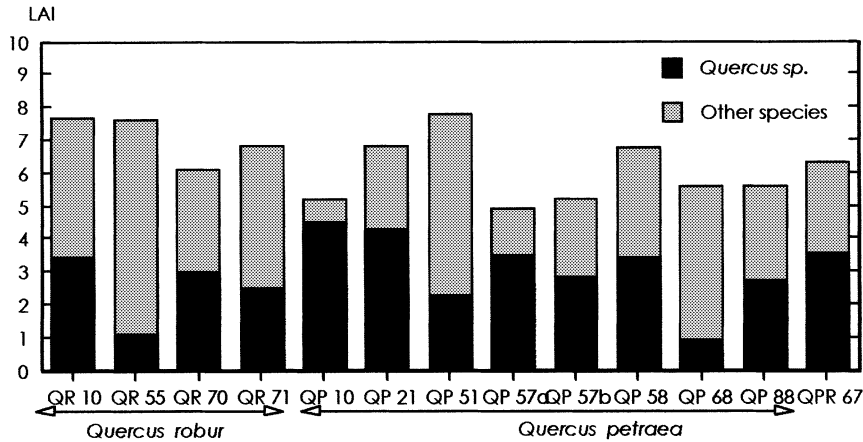

Fig. 5. Variability of leaf area index (*LAI*) among 13 oak stands in the Intensive Monitoring of Forest Ecosystems network in Europe (Level II, RENECOFOR). Leaves were sorted according to the species after collection, and specific leaf areas were estimated separately for each species. QR is for *Quercus robur*, QP for *Quercus petraea* and QPR for mixed stand. In many oak stands, secondary species contributed of the largest fraction of total *LAI* (Bréda, unpublished data).

are used to derive *LAI* (Fig. 6). Several authors have discussed how to determine *k* (Ledent, 1977; Smith, 1993; Vose *et al.*, 1995; Hassika *et al.*, 1997) and the accuracy of the method (Nel and Wessman, 1993). Pierce and Running (1988) proposed the use of a constant *k* value of 0.52 for coniferous species based on measurements by Jarvis and Leverenz (1983). The extinction coefficient also depends on stand structure and canopy architecture (Turton, 1985; Smith *et al.*, 1991; Dufrêne and Bréda, 1995). Campbell (1986) and Thomas and Winner (2000) ascribed 10% of the variation in *LAI* to the effects of alternative assumptions of distribution of foliage inclination. Comeau *et al.* (1998) have discussed integration over time and effects on *LAI* calculation. The canopy extinction coefficient is a function of wavelength (Jones, 1992), radiation type and direction (Berbigier and Bonnefond, 1995). It is also important to maximize spatial integration by the use of large sensors, linear sensors or mobile sensors. Some *k* values are listed in Table 1 for coniferous and broad-leaved stands. The variation is such that the *k* coefficient would better be estimated for every stand (Johansson, 1989; Cannell *et al.*, 1989; Smith *et al.*, 1991).

In conclusion, the monitoring of seasonal transmittance remains one of the most efficient ways of daily monitoring both *LAI* increases and decreases. These two highly dynamic phases are difficult to survey with manual measurements, but are essential for the calculation of the seasonal time-course of energy fluxes. As an example, the progression of transpiration as *LAI* expands during spring in an oak stand has to be monitored with a daily resolution (Fig. 7). Other smaller *LAI* fluctuations, induced by successive flushing or by pest damage, could also be detected, dated and quantified by this method. Such measurements, nevertheless, often remain spatially limited by the number of below-canopy sensors used. An interesting answer may be to use a mobile sensor allowing both continuous and spatially integrated light measurements.

Commercial canopy analysers: Four commercial canopy analysers are available for measuring the fraction of transmitted radiation that passes through a plant canopy. Two of them are suitable for operating in the sunfleck or the irradiance mode in the *PAR* waveband (SunSCAN, Delta-T Devices Ltd, Cambridge, UK;
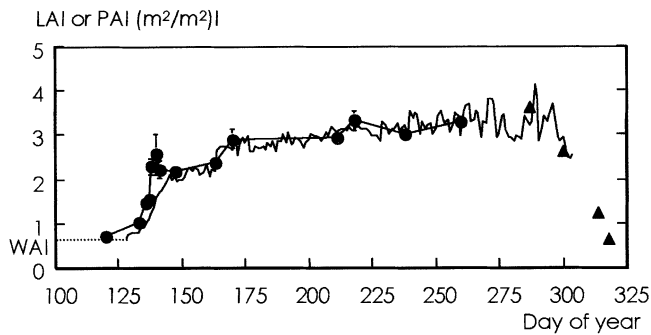
Fig. 6. Seasonal time-course of leaf area index (*LAI*) calculated from global radiation interception (line, extinction coefficient=0.29 derived from direct *LAI*$_{\text{allometry}}$ of 3.9) and from litter collection during the fall (black triangles) in a 45-year-old sessile oak stand recently thinned. Plant area index (*PAI*) was also measured periodically with the Demon instrument (black circles). The wood area index (WAI) was measured before bud break (computed from Bréda *et al.*, 1995; Dufrêne and Bréda, 1995).

Table 1. *Values of extinction coefficient for global radiation measured in coniferous and broad-leaved stands (from Bréda et al., 2002)*

Coniferous stands	k	Broad leaved stands	k
Abies sp.	0.31	*Betula* sp.	0.57
Larix sp.	0.32	*Eucalyptus globulus*	0.50
Picea abies	0.28–0.37	*Fagus* plantation	0.40–0.48
Pinus contorta	0.29–0.56	*Fagus sylvatica*	0.43–0.44
Pinus radiata	0.50	*Larix decidua*	0.58
Pinus resinosa	0.42	Mixed broadleaved	0.50
Pinus strobus	0.45	*Nothofagus solandri*	0.42
Pseudotsuga menziesii	0.40	*Quercus petraea*	0.29–0.58
Average	0.40	Average	0.47

AccuPAR, Decagon Devices, Pullman, USA) and the two others measure the gap fraction for different zenithal angles. The LAI-2000 (Li-Cor, Lincoln, Nebraska, USA) measures in five zenith angles simultaneously, through a fish-eye light sensor, while the DEMON instrument (CSIRO, Canberra, Australia) measures direct beam radiation from the sun through a directional narrow angle of view (0.302 sr). Measurements with the DEMON instrument have to be repeated several times from early morning until noon to collect data over a range of zenith angles. The main characteristics of these instruments are listed in Table 2.

The SunScan and AccuPAR (Decagon Devices, Pullman, USA) are two instruments that measure the incident photosynthetic active radiation (*PAR*) and the transmitted *PAR*. Both instruments were developed and optimized for low and regular canopies. The probe for the below-canopy measurement is a linear sensor including 64 or 80 equidistant calibrated photodiodes measuring in the *PAR* waveband (400–700 nm). Each photodiode can be logged individually if sunflecks are to be estimated or used to provide an average reading along the probe. Both instruments can work with alternative above- and below-canopy *PAR* measurements using only the linear probe. The SunSCAN probe can also be connected to a Beam Fraction Sensor (BFS) measuring both direct and diffuse incident radiation above the canopy and simultaneously connected to the common logger of the linear probe. This configuration is unsuitable for *LAI* measurements in tall canopies, for which application Delta-T proposes two alternatives: the first is to replace the cable connection between the BFS and the SunScan probe by a radio link. The effective distance between the two sensors using such a transmission should be worth testing under forest canopies as it may reach only 150–200 m (Ecotechnic, personal communication). The second option is to disconnect the BFS and to connect it to an independent data logger. These options work but increase the equipment cost and the advantage of the real-time *LAI* calculation and display is lost.

The Plant Canopy Analyser, LAI-2000 has been widely used for the ecophysiology of agricultural crops (Hicks and Lescano, 1995), coniferous stands (Gower and Norman, 1991; Deblonde *et al.*, 1994) and deciduous stands (Dufrêne and Bréda, 1995; Cutini *et al.*, 1998; Le Dantec *et al.*, 2000). The simplest way to measure below- and above-canopy radiation is to use two cross-calibrated sensors connected to the same data logger, one devoted to above-canopy measurements, the other moving below the canopy. Another procedure consists of alternating below- and above-canopy measurements with a single sensor. For tall canopies such as forests, the

above-canopy measurement is critical and limits the use of the instrument as an open area has to be found (theoretically with a diameter at least seven times the canopy height), which is generally only available far from the stand (outside the forest). To reduce the size of this required open area, view caps, providing azimuthal masking into several quadrants, are available. Another way to proceed is to use two cross-calibrated sensors and two synchronized loggers. In any case, these solutions are expensive and negate the advantage of the real-time *LAI* calculation and display. Another precaution is to perform measurements in diffuse radiation (i.e. under a uniformly overcast sky or a clear sky at sunset or sunrise). Figure 8 shows that *PAI* from LAI-2000 measurements underestimates *LAI* established by litter collection in beech stands.

The Demon uses an extension of the point quadrat method (Warren Wilson, 1959, 1960, 1963), where the direct beam of the sun replaces the needle. Surprisingly, this instrument is little used in spite of its performance and its ease of use in forestry, agronomy and horticulture (Lang *et al.*, 1990, 1991; Brenner *et al.*, 1995; Fassnacht *et al.*, 1994; Dufrêne and Bréda, 1995; Berbigier and Bonnefond, 1995; Fig. 6). In tall canopies, the operator moves beneath the canopy along a linear path, keeping the sensor oriented to the sun with the help of a sight. This is easy to do in most forest stands. In crops, the sensor is driven along a track beneath the canopy, still aimed at the sun. To compute the transmittance, the direct incident radiation has to be measured in a fixed position, which can be done in a small canopy gap because of the reduced viewing angle of the sensor. This is a clear advantage for *LAI* measurements in forest stands where only small open areas are available. Gap fraction is computed by logarithmic averaging of the transmittances of subgroups of the data (Lang, 1986, 1987). Gap fraction is finally expressed as a function of solar angle, and the measurements have to be repeated several times from early morning until noon. Figure 6 shows good agreement in the seasonal time-courses in an oak stand of *PAI* as measured with a DEMON instrument and *LAI* by global radiation interception and litter collection. Figure 9 compares direct *LAI* estimates with indirect *PAI* measurements by LAI-2000 and Demon canopy analysers. Good agreement between *LAI* and Demon-*PAI* is observed, while the best agreement between *LAI* and LAI-2000 *PAI* is obtained for a calculation using only the three upper rings (0–43° from zenith) of the hemispherical sensor (Dufrêne and Bréda, 1995).

Canopy analysis systems based on hemispherical image analysis: Fish-eye photography (and related hemispheric view analysis) has been used for a long time to describe canopy structure, to map and quantify radiation microclimate below canopies, to calculate solar radiation indices (Anderson, 1964; Becker, 1971; Ducrey, 1975*a*, *b*),
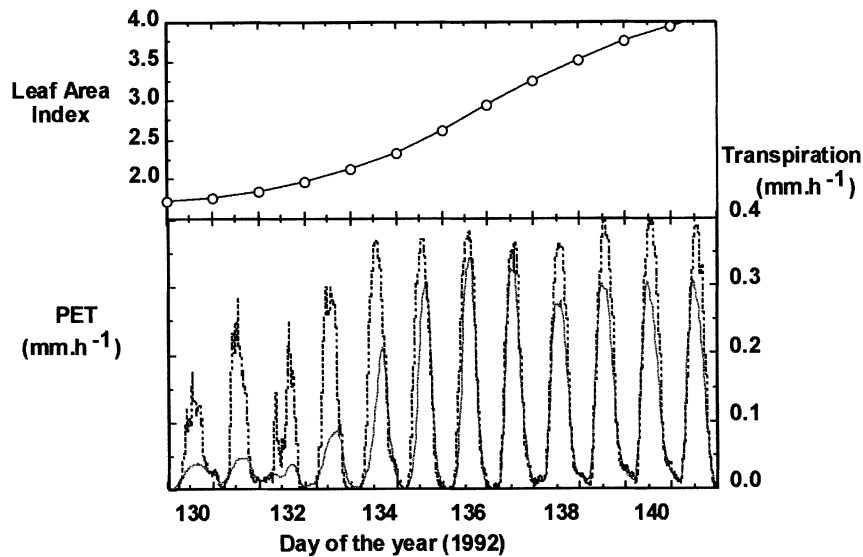
Fig. 7. Progression of stand transpiration (continuous line) compared with potential evapotranspiration (PET, dashed line) during spring *LAI* expansion, calculated from global radiation interception (from Bréda and Granier, 1996).

and, afterwards, to estimate the canopy leaf area index (Bonhomme, 1970, 1993; Bonhomme *et al*., 1974; Rich, 1990). Recently, classical fish-eye photography has been used to assess horizontal (Walter and Grégoire-Himmler, 1996) or vertical (Soudani *et al*., 2002) hetero-geneity in canopies, but without validation by direct measurements. Hemispherical photography can also be used from above the canopy looking downward. In that case, bare soil has to be distinguished from woody material and live green vegetation by using reflectance ratios (Barnsley *et al*., 2000). However, as it involves many time-consuming steps from photography to *LAI* calculation, fish-eye photography was progressively forsaken for canopy analysers. Nevertheless, with the development of high-resolution digital cameras and advances in image processing software, there has been a renewal of interest in this method. To date, few published data are available to assess the performance of digital pictures compared with classical ones from film (Frazer *et al*., 2001). The following section will briefly compare three available commercial integrated instruments from photography through to *LAI* calculation (Table 3). Free software is available for computing *LAI* from any fish-eye photograph (GLA Gap Light Analyser from Gordon W. Frazer or WinPhot from Hans ter Steege). Information about the available tools may be obtained directly from the authors at www.bio.uu.nl/ ~boev/staff/personal/htsteege/htsteege.htm or www.rem.sfu.ca/ forestry/gla/gla_info.htm. Whatever the analysis system, hemispher-ical photographs with both digital and 35 mm images from film cameras must be taken under uniform sky conditions such as exist just before sunrise or sunset or when the sky is evenly overcast. The most critical step in image processing is probably determining the threshold between the sky and canopy elements.

Both WinSCANOPY (Regent Instruments Inc., Quebec, Canada) and HemiView (Delta-T Devices Ltd, Cambridge, UK) are canopy analysis systems based on coloured hemispherical images. Their standard systems include a digital camera, a calibrated fish-eye lens to add to the standard camera and a self-levelling system. The systems do not require above-canopy measurements. Images are taken in the field and processed externally using specific software from each company. They calculate canopy parameters according to Norman and Campbell (1989), such as leaf area index (but not with the basic WinSCANOPY version), leaf-angle distribution and mean leaf angle, angular distribution of gap frequencies, and site factors

(direct, diffuse, and global). It can also predict radiation values beneath the canopy. Most of the outputs are available by sky sector or aggregated into a single overall whole sky or annual value.

The digital plant canopy imager CI-110 is quite different because it takes and processes coloured hemispherical images in real-time in the field. The hemispherical lens is mounted on an auto-levelling design on the tip of a handle connected to a portable computer devoted to the equipment. The sensor plus auto-levelling system is 10 cm high, therefore no image can be captured at ground level. The CI-110 uses a digital camera to zoom and focus to gain a detailed picture of the canopy with a resolution of 640×480 pixels. No reference is needed. Pictures can be saved and analysed either in the field or in the laboratory. With the help of the software included for image processing, the operator can define the grid size by choosing a number of both zenithal angles and azimuthal divisions in the range of one to ten each. The software computes leaf area index from the gap fraction inversion procedure according to Norman and Campbell (1989), sky view factor, mean foliage inclination angle, foliage distribution and extinction coefficient of the canopy. No published results of cross-comparison among these instruments and software are available yet.

Current controversial issues

Several papers have compared plant area index as meas-ured by indirect methods with direct *LAI* estimates (Neumann *et al*., 1989; Chason *et al*., 1991; Lang *et al*., 1991; Smith *et al*., 1993; Fassnacht *et al*., 1994; Dufrêne and Bréda, 1995; Vertessy *et al*., 1995; Comeau *et al*., 1998; Küßner and Mosandl, 2000). Most of these papers concluded that indirect methods underestimated *LAI* compared with direct measurement. The reported under-estimate varies from 25% to 50% in different stands (Gower and Norman, 1991; Cutini *et al*., 1998; Gardingen *et al*., 1999; Gower *et al*., 1999). It is now widely accepted that a reason for the underestimation is the non-random distribution of foliar elements within the canopy. The

Table 2. *Characteristics of different commercial canopy analysers*

	SunScan	AccuPAR	LAI-2000	DEMON
Company	Delta-T Devices Ltd, Cambridge, UK	Decagon Devices, Pullman, USA	Li-Cor, Lincoln, Nebraska, USA	CSIRO, Canberra, Australia
Reference web site	www.delta-t.co.uk	www.decagon.com	www.licor.com	www.cbr.clw.csiro.au/pyelab/tour/demon.htm
Principle	Gap fraction or sunflecks	Gap fraction or sunflecks	Gap fraction for each zenith angle acquired simultaneously	Gap fraction zenith angles from the sun at different angles to the vertical
Type of radiation	Direct and diffuse *PAR*	Total *PAR*	Diffuse blue light	Direct sun beam
Waveband	400–700 nm	400–700 nm	320–490 nm	430 nm
Above-canopy measurement (A)	Incident direct and diffuse *PAR* BFS1: 1 direct *PAR* sensor, 1 diffuse *PAR* sensor with shade-ring BF2: 7 photodiodes+dome	Linear *PAR* ceptometer Alternative above- and below-canopy *PAR* measurements	Above canopy or open area (diameter 7× canopy height) or view caps for azimuthal masking	Sensor pointed to unobstructed sun (small open area), fixed position
Below-canopy measurement (B)	Transmitted direct and diffuse *PAR* SunSCAN probe	Transmitted direct and diffuse *PAR*	Fixed position	Averaged transmittance moving on foot along 20 m paths
Reference and algorithms	Campbell, 1986 Potter et al., 1996	Campbell, 1986 Decagon, 2001	Welles and Norman, 1991 Li-Cor, 1989	Lang, 1986, 1987 Lang and Yueqin, 1986
Sensor	64 *PAR*-sensors distributed along a 1-m rod	80 *PAR*-sensors distributed along a 0.90-m rod	Fish-eye sensor with five concentric light-detecting rings in five zenith angles	Detector sighted at the sun (narrow cone of angle 0.302 sr)
Calibration	*PAR* calibrated	*PAR* calibrated	Not calibrated but possible calibration, see Hanan and Bégué (1995) or Comeau *et al.* (1998)	Not calibrated
Option for crop canopies	Well suited	Well suited	2 loggers + 2 cross-calibrated sensors or alternate A and B measurements	None, but well suited
Option for tall canopies	Disconnect A sensor, radio transmission or data logger	Large open area	Minimum distance between sensor and leaves (4× leaf width)	Option for single tree Driving the detector along a 3 m long track beneath canopy
Sky condition	Wide range of daylight conditions, best in bright daylight	Wide range of daylight conditions, best in bright daylight	Uniform overcast sky or clear sky at sunset or sunrise	Clear bright day from early morning until noon
Software	SunDATA.exe	DecaLink, AccuPAR firmware	C2000.exe	DEMSOFT 1/LONETREE

degree of error in the *LAI* measurement is a result of the canopy's deviation from this assumption of random dispersion, which was named 'clumping' (Nilson, 1971; Lang, 1986, 1987; Kucharik *et al.*, 1997; Chen *et al.*, 1997). Many solutions have been proposed to overcome this clumping bias.

The first proposal was from Nilson (1971), who introduced a correction factor Ω in the formulation of

gap fraction. Chen *et al.* (1991) proposed a new term for effective *LAI* (L_e), which equals to the product of Ω by *L*, where *L* represents the actual *LAI* (equal to a harvested *LAI* measurement) and Ω refers to a clumping index describing the non-random distribution of canopy elements. When a canopy displays random dispersion, Ω is unity; when a canopy is clumped, Ω is higher or lower than unity. More recently, several papers (Chen *et al.*, 1991, 1997; Fournier

et al., 1997; Walter and Torquebiau, 1997) reported that clumping occurs at several scales, between plants within a stand, and between branches or shoots within plants. The clumping factor was then divided into two components: Ω_e is the between-shoots clumping factor and γ_e is the within-shoot clumping factor.

Two new instruments have been developed to measure the between-shoot clumping factor Ω_e: the TRAC (Tracing Radiation and Architecture of Canopies) developed by Chen *et al.* (1997) and the MVI (Multiband Vegetation Imager) developed by Kucharik *et al.* (1997). Table 4 compares the main characteristics of these two instruments. The spatial resolution of both devices is wider than

LAI or PAI (m²/m²)

Fig. 8. Comparison between leaf area index (*LAI*, litter collection, 10 traps) and plant area index (*PAI*, LAI-2000, Li-Cor, Lincoln, Nebraska, USA, 10 below-canopy measurements) for seven beech plots in the Intensive Monitoring of Forest Ecosystems network in Europe (North-East part of France, RENECOFOR). Both *PAI* and *LAI* compared well without correction for wood area index. The dominant species (beech, *Fagus sylvatica*) contributed most to the total *LAI*. *PAI* measured with the LAI-2000 underestimates *LAI* from litter collection. The especially large underestimation of *PAI* for plot HET54b was due to a dense regeneration. Traps collected litter of seedlings from natural regeneration, while *PAI* measurements were performed above the seedlings (Bréda, unpublished data).

within-branch gaps, so that they both measure Ω_e. Quantification of γ_e requires laboratory measurements.

Clumping factors estimated by the TRAC have recently been validated (Chen and Cihlar, 1995; Chen, 1996; Chen *et al.*, 1997; Kucharik *et al.*, 1997). The TRAC device is suitable for computing *PAI*, but Chen *et al.* (1997) advised correcting indirect *LAI* measurements (e.g. from the LAI-2000) using the clumping factor derived from TRAC estimates. Both instruments have recently been used to derive the ground-based *LAI* and to validate remotely sensed indices in Canada (Chen *et al.*, 2002). The *PAI* derived from MVI has been validated against allometric *LAI* (Kucharik *et al.*, 1998a, 1999) and the clumping factors estimated by the MVI have been compared with independent measurements. Some values of between-shoot clumping factor (Ω_e), as estimated using either TRAC or MVI, are listed in Table 5. The between-shoot clumping factor estimated from TRAC measurements is twice as large as the MVI ones. According to Kucharik *et al.* (1999), this was due to differences in maximum gap sizes and gap-size distributions in conifers obtained at different measurement angles, because the canopy gap-size distribution is dependent on zenith angle. In these studies, gap-sizes were measured at solar zenith angles of 30–70° with TRAC, while towards the zenith with MVI.

Several authors suggested that indirect methods measured a shoot area index not a leaf (or needle) area index (Gower and Norman, 1991; Chen, 1996; Chen *et al.*, 1997). The leaf area index should be calculated simply as the product of indirect measurement by the within-shoots clumping factor (γ_e) according to Gower and Norman (1991). They first used the ratio between total projected area of needles and shoot projected area for coniferous
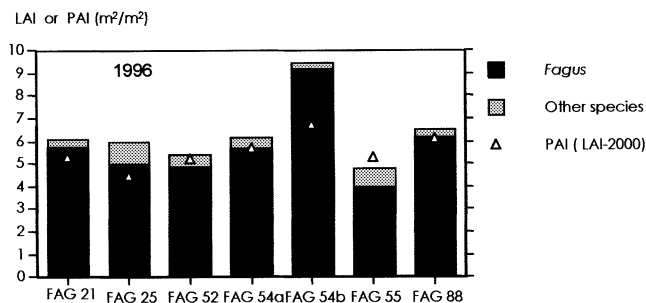

Fig. 9. Comparison between direct leaf area index (*LAI*) estimated by litter collection and plant area index (*PAI*) measured with the LAI-2000 and DEMON canopy analysers (left) and comparison between *PAI* measured by Demon and LAI-2000, including both winter (*WAI*) and summer (*PAI*) measurements (right). Each point represents a beech or an oak stand, bars are 95% confidence intervals, *PAI* from LAI-2000 was calculated using values from ring 1 to 3 (0–43° from zenith). The 1:1 line is fitted. (from Dufrêne and Bréda, 1995).

trees. Their ratios are used in the LAI-2000 user's manual (Li-Cor, 1992) and equal 1.5 (±0.41), 1.61 (±0.35), 1.49 (±0.28), and 1.6 (±0.14), for *Pinus resinosa*, *Pinus strobus*, *Larix decidua*, and *Picea abies*, respectively. Fassnacht *et al*. (1994), Stenberg *et al*. (1994) and Chen (1996) pointed out that these authors measured the clumping factor using a single vertical projection. They noted that the projected area depends on both shoot inclination and radiation direction and suggested a new method to quantify the clumping. Table 6 indicates some clumping factors γ_e as estimated by multi-angular projection. In deciduous forests, the value of γ_e is 1.0, while in conifers values of γ_e are typically between 1.2 and 2.0 (Kucharick *et al*., 1998*b*). This is due to the distribution of branches, shoot and needles whorls being highly non-random.

Table 3. *Main characteristics of canopy analysis systems based on hemispherical images analysis (WinSCANOPY, HemiView and the Digital Plant Canopy Imager, CI-110)*

	WinSCANOPY	HemiView	CI-110 Imager
Company	Regent Instruments Inc., Quebec, Canada	Delta-T Devices Ltd, Cambridge, UK	CID Inc., Vancouver, USA
Reference web site	www.regent.qc.ca	www.delta-t.co.uk	www.cid-inc.com
Camera	CCD camera (Nikon, Coolpix) with self-levelling system	Digital camera or 35 mm film camera with self-levelling system	Ci-110LLP precision digital fish-eye probe
Lens	Fish-eye lens (180°) to add to the standard camera lens		Lens with self-levelling system
Image resolution	Depending on camera and file format (640×480 to 2.048×1.536 pixels)		640×480 pixels
Algorithm for *LAI* calculation		Norman and Campbell (1989)	
Outputs	Basic: Openness, gap fraction	*LAI*, leaf-angle distribution, angular distribution of gap frequencies, site factors	*LAI*, gap fractions, sky view factor, mean foliage inclination angle, foliage distribution, *k*
	Regular: + *LAI*, LAD, site factors Pro: + gap size and position		
Calibration	Lens calibrated (field of view, lens centre, boundaries of the field of view)	Not indicated	Factory calibration
Particularities	Magnetic north finder	Software option: leaf area of single tree	*PAR* sensor
Sky condition	Uniform overcast sky or clear sky at sunset or sunrise		Capture and analyses fish-eye images in the field
Software	WinSCANOPY (3 versions) SCANOPY XLSCANOPY	HemiView analysis software	Windows software package

Table 4. *Comparison of characteristics of two instruments, Tracing Radiation and Architecture of Canopies (TRAC) and Multiband Vegetation Imager (MVI), for measuring between-shoot clumping*

	Tracing Radiation and Architecture of Canopies (TRAC)	Multiband Vegetation Imager (MVI)
Company	Third-Wave Engineering, Ottawa, Canada	SpectraSource Instruments Westlake Village, Canada
	mikek@3wce.com	
Reference website	www.ccrs.nrcan.gc.ca/ccrs/tekrd/rd/apps/em/beps/trac_e.html	daacl.esd.ornl.gov/boreas/TE/te6mltvg/comp/TE06 Multi Veg Imager.txt
References and algorithms	Chen, 1996 Chen *et al*., 1997	Kucharik *et al*., 1997 Kucharik *et al*., 1998*b*
Principle	Transmitted *PAR* and sunfleck length	Images in two different wavelength bands
Measurement mode	User walking regularly beneath the canopy along 200–300 m paths	Picture capture at fixed positions beneath the canopy
Waveband	400–700 nm	Visible band 400–620 nm Near-infrared band 720–950 nm
Technics	High frequency (32 Hz) monitoring of transmitted *PAR* along 200–300 paths	Digital camera with a 24 or 35 mm lens + filters
Outputs	Between-shoot clumping Ω_e, *PAI*	Between-shoot clumping Ω_e, *PAI* Exposed and shaded leaves and branches, angular distribution of gap fraction, WAI
Sky conditions	Clear sky whatever the solar's elevation	

Table 5. *Between-shoot clumping factor (Ωe) as estimated by TRAC and MVI instruments*

Species	Age (years)	Height (m)	Stand density (trees ha^{-1})	Clumping Ω_e
Pinus banksiana	60–75	12–15	1600–2400	0.71 TRAC[a]
Pinus banksiana	11–16	4–5	400–4100	0.71 TRAC[a]
Pinus banksiana	50–65	9–13.5	1300–2600	0.82 TRAC[a, b] 0.45 MVI[b]
Pinus banksiana	25	0–2.5	5700–42 000	0.95 TRAC[a]
Picea mariana	0–155	0–11	3700–4400	0.70 TRAC[a ,b] 0.35 MVI[b]
Populus tremuloides	–	–	–	0.72 TRAC[b] 0.64 MVI[b]
Acer saccharum	–	–	–	0.95 MVI[c]
Quercus	–	–	–	0.88 MVI[c]
Tsuga canadensis	–	–	–	0.94 MVI[c]

[a] Chen, 1996.
[b] Kucharik *et al.*, 1999.
[c] Gower *et al.*, 1999.

Table 6. *Values of within-shoot clumping factor (γe) measured by multi-angular projection*

Species	Clumping factor	Source
Acer saccharum	1.0	Gower *et al.* (1999)
Quercus	1.0	Gower *et al.* (1999)
Quercus	0.9	Kucharick *et al.* (1999)
Acer saccharum	0.9	Kucharick *et al.* (1999)
Populus tremuloides	1.0	Gower *et al.* (1999)
Pinus banksiana	1.3	Chen and Cihlar (1995)
Pinus banksiana	1.2–1.4	Gower *et al.* (1999)
Picea mariana	1.3–1.4	Gower *et al* (1999)
Pseudotsuga menziesii	1.77	Smith *et al.* (1993)
Pinus sylvestris	1.75	Stenberg *et al.*(1994)
Pinus resinosa	2.8	Chen and Cihlar (1995)

This last source of discrepancy between direct and indirect measurement is specific to forests and shrubs. All the indirect optical methods calculate a Plant Area Index, because they include the contribution of stems and branches. Figure 10 shows an example of variability among oak stands of both *PAI* measured at maximum *LAI* and Wood Area Index measured during winter. Wood Area Index ranges from 0.43 to 2.45. Taking into account both clumping and woody parts, Chen (1996) expressed the effective *LAI* (L_e) as (Ω_e/γ_e) *PAI*. Leaf area index (*LAI*), strictly, is the difference between *PAI* and wood area index, *WAI*: $LAI=PAI–WAI=PAI(1–\alpha)$ where α is the ratio of *WAI* to *PAI* or $LAI=(1–\alpha) L_e \gamma_e /\Omega_e$. *LAI* is the measured parameter using direct methods, while indirect methods compute L_e. The accurate estimation of *LAI*, therefore, requires the determination of the contribution of both clumping and woody parts. Several studies have attempted to estimate *WAI* either directly or indirectly (Table 7). The recent review by Gower *et al.* (1999) makes these main points: (1) the contribution of woody parts to *PAI* as measured by indirect methods ranges from 5–35% and (2) *PAI* has then to be corrected. Nevertheless, the procedure for deriving *LAI* from *PAI* is still a much debated question.

Lang (1991) and Chen (1996) thought that *PAI* equals the addition of *LAI* to WAI whereas Dufrêne and Bréda (1995) and Gower *et al.* (1999) emphasized that this equality is not general because of the overlapping of branches by leaves. Dufrêne and Bréda (1995), using an indirect versus direct method calibration in deciduous stands, concluded that the *PAI* calculated by the LAI-2000 using the three upper rings (0–43° from zenith) was equivalent to direct *LAI* measurements from litter without any correction.

Sampling strategy

The sampling strategy used to record *LAI* is probably as crucial as the technical choices for measurements. Common to all methods and instruments is the question of spatial and temporal relevance of *LAI* measurements. Parameters like canopy height and vertical stratification, plot dimensions, site topography, spatial integration of sensors, and canopy continuity (close, randomly dispersed or regular geometric designs, isolated plant) are of importance for the procedure used and for the reliability of the result. The timing of sampling is related to the natural or incidental seasonal time-course of *LAI*. For both spatial and temporal sampling strategies, advice can be given about field measurement design and the choice of algorithms to compute *LAI*.

For litter collection, the number of traps and their arrangement are basic questions for sampling. Traps of various dimensions and shapes may be used (square or circular, ranging from 0.18–1 m^2), with drainage holes to slow down leaf decomposition. Depending on leaf size, a large number of small traps should be preferred to a few large traps (Aussenac, 1969; McShane *et al.*, 1983; Morrison, 1991). Several sampling strategies (number and size of traps) have been reported (Burton *et al.*, 1991; Vose *et al.*, 1995), but traps are commonly distributed according to a systematic network. Recently 32 protocols used in the EC for forest ecosystem monitoring were gathered and analysed (Bréda and Landmann, 2001). The
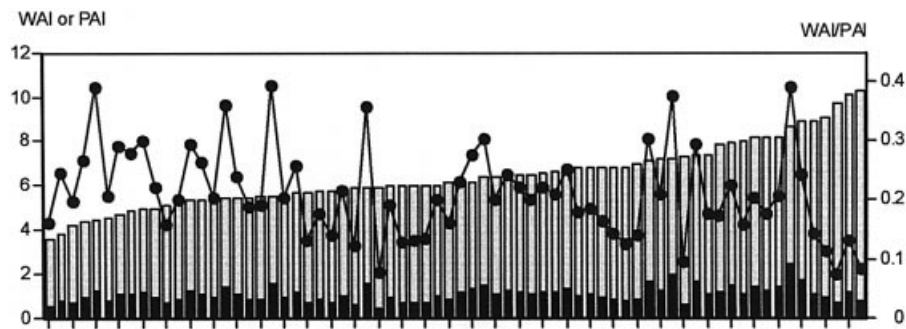
Fig. 10. Wood area index (*WAI*, black bars) measured during the leafless period and plant area index (*PAI*, grey bars) measured in June (maximum *PAI*) in 70 oak stands from the Harth Forest (France). Both *WAI* and *PAI* were measured using the LAI-2000 and calculations were carried out with the three upper light-detecting rings of the fish-eye sensor. The plots are sorted according to increasing *WAI*+*PAI*. The *WAI:PAI* ratio (black circles) ranges from 0.07 to 0.40 and it tends to decrease as the *PAI* increases. (Bréda, unpublished data).

Table 7. *Values of wood area index (*WAI*) and wood area index/plant area index proportion expressed as a percentage (*WAI/PAI*)*

Species	Method	*WAI*	*WAI/PAI* (%)	Source
Pinus radiata	Direct harvesting		14.5	Lang *et al.* (1991)
Chamaecyparis optusa	Direct harvesting	1.35	12	Hagihara and Yamaji (1993)
Pinus resinosa	Direct harvesting		8–12	Deblonde *et al.* (1994)
Pinus banksiana			10–33	
Picea mariana	Direct harvesting		28–32	Chen (1996)
Pinus banksiana			3–5	
Pinus sylvestris	Hemispherical photography		10	Walter and Grégoire-Himmler (1996)
Pseudostuga meziesii	LAI-2000	2.14	41	Barclay *et al.* (2000)
Acer macrophyllum	defoliated versus	1.00	41	
Alnus rubra	non-defoliated trees	0.80	25	
Quercus sp. and *Fagus sylvatica*	LAI-2000 and Demon	0.26–1.52	20–40	Dufrêne and Bréda (1995)
Quercus cerris, Fagus sylvatica,	LAI-2000	0.50–1.00	9–38	Cutini *et al.* (1998)
Capinus betulus				
Quercus sp. stands	LAI-2000	0.43–2.45	7–40	This paper (Fig. 10)

litter-fall collecting designs involved from 20 to 40 collectors (33 traps ha^{-1} on average) with a collecting area ranging from 0.25–1 m^2 (0.45 m^2 on average). In that study, the sampling rate (cumulative sampling area divided by plot area) ranged from less than 0.1% up to 2%. Specific designs should be adopted for sloping sites (Welbourn *et al.*, 1981) or mixed stands (Ferrari and Sugita, 1996).

Before defining a sampling design for both hemispherical photography and indirect methods, the minimum plot area (for both below- and above- canopy measurements) has to be evaluated using geometric calculation, taking into account canopy height, sensor angle of view, and distance to the edge of the stand (Chason *et al.*, 1991; Nackaerts *et al.*, 2000). Specific designs and precautions should be adopted for slope, such as holding the sensor parallel to the slope; computation procedures for *LAI* with fish-eye sensors have been specifically proposed for sloping sites (Walter and Torquebiau, 2000). The spatial variability of the canopy structure in communities then has to be assessed and allowed for in the measurement design to minimize the impact of clumping. For close or randomly

dispersed canopies, a systematic or random distribution of below-canopy measurements is suitable. In the case of regular geometric designs (row crops or tree lines in plantations), below-canopy measurements have to be distributed along diagonals between rows. Special attention has to be paid to the compass orientation of rows and to significant gaps in the structure. In the case of discontinuous and heterogeneous canopies, such as forests with open areas, row crops before canopy closure or sparse canopies that never close, the previously mentioned underestimation of *PAI* as compared with direct *LAI* is especially large. Lang *et al.* (1985) evaluated the effect of plantation lines on indirect *LAI* measurement and suggested that logarithmic averaging would be more suitable for inverting the gap fraction (Lang, 1986). Lang and Yueqin (1986) finally proposed a procedure for averaging logarithms of transmittance in order to accommodate gaps in the canopy. Levy and Jarvis (1999) confirmed the performance of Lang and Yueqin's (1986) algorithm in minimizing the effect of clumping in sparse and highly clumped canopies of millet row crops. Finally, it may be

suggested that the developed algorithms for calculating clumping (Chen *et al.*, 1997; Kucharik *et al.*, 1997) could be applied to individual *PAR* measurements along the linear path of AccuPAR or SunScan instruments; this should also be expanded to the DEMON if individual scans instead of averages could be logged. The incorporation of clumping algorithms may improve the performance of these instruments.

Other sampling difficulties arise for *LAI* measurement on single trees, shrubs, dwarf shrubs and herbs. For individual trees growing singly or in groups, Norman and Welles (1983) proposed to replace the term *LAI*/cos(θ) with (*ds*), where *d* is the leaf area density within the crown and *s* is the distance through the tree crown along which the beam passes. According to Whitehead *et al.* (1990) for individual tree crowns:

$$P(\theta) = \exp(-kds) \tag{5}$$

k is the fraction of leaf area that is projected on a plane normal to the beam: *k* equals 0.5 if leaf-angle distribution is assumed to be spherical (Ross, 1981). The leaf area density is the foliage area divided by canopy volume, which requires additional dendrometrical measurements. The leaf density has the dimension of inverse length (m^{-1}).

Direct methods might be preferred (Nowak, 1996) because indirect methods are not suitable for single plants, although LONETREE with Demon equipment (Lang and McMurtrie, 1992) or Hemiview software propose specific options for *LAI* measurements on a single tree. The LAI-2000 user's manual also suggests how to measure the *LAI* of an isolated plant (Li-Cor, 1992). In the case of direct methods for single plants, total plant harvesting is the most efficient strategy, because sub-sampling of leaves within the crown requires care, for example, specific leaf area changes between sun-exposed and shaded leaves or according to orientation within the canopy (Cermak, 1998).

Seasonality has temporal implications for the sampling strategy. First, all radiation-based methods are influenced by the seasonal time-course of solar elevation and diffuse versus direct radiation ratio. As an example, the derivation of a seasonal time-course of *LAI* from radiation interception monitoring requires that only days with similar direct/diffuse proportion of radiation be selected, following Spitters *et al.* (1986). Moreover, measurements at the beginning and the end of each day are best eliminated, as the transmittance changes as a result of larger fractions of diffuse radiation. Moreover, *LAI* itself exhibits a seasonal progression, especially from *WAI* to *PAI* for deciduous species, but also in coniferous stands and tropical forests (Wirth *et al.*, 2001): expansion of new leaves is not necessarily concomitant with the fall of older ones. In mixed deciduous and coniferous stands, winter measure-ment leads to a complex *PAI* including *LAI* of coniferous trees and *WAI* of deciduous ones. Another seasonal example is the canopy closure in row crops, with the regular geometric design progressively disappearing as the canopy develops. As a consequence of seasonality, extinction coefficient (Cannell *et al.*, 1989; Norman and Campbell, 1989; Smith *et al.*, 1991; Berbigier and Bonnefond, 1995), *PAI* versus *LAI* ratio (Dufrêne and Bréda, 1995; Gower *et al.*, 1999), and clumping change with the season.

Conclusion and issues for the future

This literature review suggests that there are complementary approaches to describe the interaction of light with the canopy and the leaf area index measurement is only one of several canopy descriptions. Leaf area index may be measured either directly or by one of the indirect methods. Both categories of methods are complementary as calibration is still necessary for indirect methods. Recent research has attempted to improve *LAI* estimates through a better description and sampling of canopy heterogeneity (vertical and horizontal heterogeneity, clumping, canopy closure or gaps and so on). New instruments or algorithms still need to be developed to aim at converting *PAI* into *LAI* properly. It is difficult to make any generalizations, as each worker has to select the most appropriate technique for their own situation, bearing in mind the physiological process of interest. Sampling is often crucial as spatial variability in canopies is large, and replicates at several locations should always be used to determine *LAI*. For instance, the technical options are quite different if one is interested in leaf area index than if a detailed assessment of canopy geometry is also required. Finally, the main challenging point to improve *LAI* measurement should be to identify clearly the causes of its variation. The determination of *LAI* variation is an exciting topic still largely undocumented: to what extent does an individual leaf area change from one site to the other or from one year to the next? Did *LAI* fluctuation result from changes in leaf size, leaf number or both? Are there any spatial or temporal changes in leaf inclination and clumping? What is the contribution of vertical canopy structure to *LAI* variation? The answers to these questions will probably occur in the near future and contribute to new thinking on *LAI* measurements.

Acknowledgements

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