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Review of methods for in situ leaf area index determination Part I. Theories, sensors and hemispherical photography

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Abstract

Rapid, reliable and objective estimations of leaf area index (LAI) are essential for numerous studies of atmosphere–vegetation interaction, as LAI is very often a critical parameter in process-based models of vegetation canopy response to global environmental change. This paper reviews current knowledge concerning the use of direct and indirect methods for LAI determination. The value of optical LAI measurements by means of hemispherical photography has already been demonstrated in previous studies. As clumping seems to be the main factor causing errors in indirect LAI estimation, we suggest that the use of a digital camera with high dynamic range has the potential to overcome a number of described technical problems related to indirect LAI estimation. Further testing and defining of a standardised field protocol for digital hemispherical photography is however needed to improve this technique to achieve the standards of an ideal device.

Keywords: Leaf area index; Gap fraction; Hemispherical photography; Digital camera

1. Introduction

1.1. LAI definitions

Leaf area index (LAI) is a dimensionless variable and was first defined as the total one-sided area of photosynthetic tissue per unit ground surface area (Watson, 1947). For broad-leaved trees with flat leaves, this definition is applicable because both sides of a leaf have the same surface area. However, if foliage elements are not flat, but wrinkled, bent or rolled, the one-sided area is not clearly defined. The same problem exists for coniferous trees, as needles may be cylindrical or hemi-cylindrical (Chen and Black, 1992). Some authors therefore proposed a projected leaf area in order to take into account the irregular form of needles and leaves (Smith, 1991; Bolstad and Gower, 1990). However, in this case the choice of projection angle is decisive, and a vertical projection does not necessarily result in the highest values. Myneni et al. (1997) consequently defined LAI as the maximum projected leaf area per unit ground surface area. Within the context of the computation of the total radiation interception area of plant elements, and based on calculations of the mean projection

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coefficients of several convex and concave objects of different angular distributions, Lang et al. (1991) and Chen and Black (1992) suggested that half the total interception area per unit ground surface area would be a more suitable definition of LAI for non-flat leaves than projected leaf area. Their theoretical reasoning behind abandoning the projection concept was that the latter has neither physical nor biological significance, whereas the total intercepting area has a physical meaning (e.g. radiation interception) and the total area has a biological connotation (e.g. gas exchange). Still other definitions and interpretations of LAI have been proposed. These vary depending on the technique used to measure LAI. So, in current literature and next to Watson's definition, LAI defined as one half the total leaf area per unit ground surface area is being used (Chen and Black, 1991; Chen et al., 1991; Fassnacht et al., 1994; Stenberg et al., 1994). It is important to note that these different definitions can result in significant differences between calculated LAI values.

1.2. LAI in literature

The LAI of vegetation depends on species composition, developmental stage, prevailing site conditions, seasonality, and the management practices. LAI is a dynamic parameter: it changes from day to day (mostly in spring and autumn), and, driven by forest dynamics, from year to year (Welles, 1990). The sum of these factors, combined with the difference in assessment methods, may therefore lead to widely varying LAI-values as is demonstrated in the relevant literature. Published LAI-values of forests range from 0.40 for a low-density seed tree stand of *Quercus petraea* (*Matus*) *Liebl*. (Le Dantec et al., 2000) to 16.9 for an old-growth (more than 200 years) stand of *Pseudotsuga menziesii* (*Mirb*.) *Franco* (Turner et al., 2000). In general, the highest values reported previously are for particular coniferous canopies. Beadle (1993) reported that maxima between 6 and 8 are typically observed for deciduous forest and between 2 and 4 for annual crops. Schulze (1982) found that LAI for most biomes (apart from desert and tundra) ranged from about 3 to 19, the highest values being reported for boreal coniferous forest. Occasionally higher LAI-values of up to 41.8 for an evergreen broad-leaved stand (Ni et al., 2001) have been published. We suspect that these may result from inappropriate simplifications in the measurement method within of this large-scale study.

There are two main categories of procedures to estimate LAI: direct and indirect methods (see reviews of methods in Gower et al., 1999; Kussner and Mosandl, 2000). The former group consists of methods measuring leaf area in a direct way, while the latter group consists of methods where LAI is derived from more easily (in terms of time, workload, technology) measurable parameters (Fassnacht et al., 1994; Gower et al., 1999). In this review article, basic inversion theories, demonstrated advantages and disadvantages of the more frequently used direct and indirect techniques to estimate LAI in forests will be discussed. Subsequently, the focus will shift to the use of hemispherical photography for indirect LAI determination and innovative ways to alleviate the drawbacks of this particular method will be highlighted.

2. Direct LAI measurement

Direct methods are the most accurate, but they have the disadvantage of being extremely time-consuming and as a consequence making large-scale implementation only marginally feasible. Accuracy problems may in this case result from the definition of LAI, the up-scaling method, or from the error accumulation due to frequently repeated measurements. Because of its time-consuming and labour-intensive character and apart from other operational constraints, it can be said that direct LAI determination is not really compatible with the long-term monitoring of spatial and temporal dynamics of leaf area development (e.g. Chason et al., 1991). However, the need for validation of indirect methods remains, so the direct techniques can be considered important as calibration methods.

2.1. Leaf collection

LAI can be assessed directly by using harvesting methods such as destructive sampling and *the model tree method* or by non-harvesting litter traps during autumn leaf-fall period in deciduous forests. As the leaf area is determined through repeated area measurements on single leaves and area accumulation, these methods are hence considered the most accurate (Chen et al., 1997), and for that reason they are often implemented as calibration tools for indirect measurement techniques (e.g. Cutini et al., 1998). Moreover, some of the methods have the additional advantage of incorporating an evaluation of the vertical distribution of LAI within the tree crowns, though the felling and stripping of larger single trees is very labour-intensive.

Destructive sampling of a sampling plot of the stand involves up-scaling and at least the assumption of lateral homogeneity of the stand. This assumption is best met in stands of small individuals spread over relatively large areas under homogeneous conditions, like for example young conifer plantations and grasslands.

The model tree method consists of destructive sampling of a small amount of representative trees out of the stand, from which the leaf area and vertical distribution of leaf area is measured leaf by leaf. In an even-aged stand, which has often a normal distribution, sampling of three or five trees can be sufficient. While still destructive to a certain extent, the method is less disturbing at population level and therefore more convenient in forestry for stands with large trees and a lower plant density. The method has been used widely in agricultural crop assessment and forest systems, where for the latter group extrapolation can be done via allometric methods in forest stands.

Non-harvest methods consist of leaf litter collection during the leaf-fall period using what is called litter traps. Traps are open boxes with predetermined size and lateral sides preventing wind blowing leaves into/out of the traps. They are placed in the stand. A higher litter trap frequency will result in an improved accuracy as the effect of up-scaling (under the assumption of spatial homogeneity of the forest canopy) becomes less important. Traps are emptied on regular time intervals and LAI can be determined from the litter using the weight method (see Section 2.2). However, there seems to be no consensus yet on the sampling design of the traps. Some researchers advocate placing the litter traps randomly under the canopy (McShane et al., 1993), while others prefer a systematic sampling design (Dufrêne and Bréda, 1995) or transects (Battaglia et al., 1998).

Under the appropriate spatial and temporal sampling schemes, litter traps have proven very useful in deciduous forests (Neumann et al., 1989). Morrison (1991) stated that 30 traps of 1 m^2 and at a height of 1 m above the ground, are able to determine the LAI of a deciduous forest with 95% accuracy within a bias of 10% with respect to the mean. The set up is rather simple and therefore attractive, but is nevertheless not applicable to evergreen forests, where the yearly leaf fall is not directly related to the total LAI, but to the average life span of leaves and the cumulative climate conditions over that life span (Chen et al., 1997). By means of litter traps, the integrated measure for LAI over the measurement period is provided, but not an accurate measure at a single moment in time during the growing season (Neumann et al., 1989) and also climate can have an effect on the data from litter traps (Law et al., 2001).

For species that can replace their leaves during the growing season, as for example poplars, litter trap data represent an overestimation of the maximum LAI. Moreover, the method does not provide information on temporal and vertical LAI profiles, whereas the other direct methods can provide this information if properly implemented. The litter trap method is much less labour-intensive than the destructive methods, but carries the additional assumption that the foliage caught is representative for the leaf-fall of the whole stand and the tracing back to the original single trees remains however a problem. This statistical condition can only be met by incorporating a large number of litter traps per area unit.

2.2. Leaf area determination techniques

After leaf collection, leaf area can be calculated by means of either planimetric or gravimetric techniques (Daughtry, 1990). The planimetric approach is based on the principle of the correlation between the individual leaf area and the number of area units covered by that leaf in a horizontal plane. To do so, a leaf can be horizontally fixed to a flat surface, its contour can be measured with a planimeter, and its area can be computed from this contour assessment. There are different planimeters on the market for this purpose. A first type is the scanning planimeter (e.g. Li-3000, Licor, NE, USA) that uses an electronic method of rectangular approximation. The area of the leaf is measured as the leaf is drawn through the scanning head. The scanning head can be combined with a transparent belt conveyer with constant speed in order to measure large numbers of detached leaves. Other scanning planimeters (e.g. Li-3100, Licor, NE, USA) make use of a fluorescent light source and a solid-state scanning camera to "sense" the area of leaves as they move through the instrument. A portable scanning planimeter, CI-202 (CID Inc., NW Camas, WA, USA) uses a bar code reader to encode leaf length as the sensor moves along the leaf. Leaf width is measured by light reflected from the leaf to the detectors. The WinDIAS colour conveyer image analyser (Delta-T devices, Cambridge, UK) and DIAS II Digital Image Analysis System (Decagon Devices Inc., Pullman, USA) have a very high spatial resolution and are able to store and transfer images to a computer for additional analyses. A second type of planimeter is the video image analysis system, consisting of a video camera, a frame digitiser, a monitor, and a computer with appropriate software to analyse the data. Examples are DIAS (Delta-T devices, Cambridge, UK) and Decagon Ag Vision System (Decagon Devices Inc., Pullman, USA) that can provide areas, sizes, shapes, and number of leaves. An image of the flattened leaves is digitised, enhanced and analysed to discriminate the leaves from the background.

The gravimetric method correlates dry weight of leaves and leaf area using predetermined green-leaf-area-to-dry-weight ratios (leaf mass per area, LMA). LMA is determined from a sub sample extracted from the global field sample. After "green" leaf area determination using of one of the above-cited planimetric methods, the sub-sample is dried in an oven at between 75 and 105 °C until constant weight. The dry weight is subsequently determined using a precision balance and LMA is determined. Once the LMA is known, the entire field sample is oven-dried and leaf area is calculated from its dry-weight and the sub sample LMA. In order to get a homogeneous distribution of sun- and shade leaves, it has been proven of crucial importance to mix the entire leaf harvest properly prior to extracting the sub sample for LMA. Furthermore, attention must be paid to the large spatial and temporal variations in LMA values that have been shown to occur within many tree species. For example, LMA varies significantly with branch age, light exposure, and canopy height (Klein et al., 1991; Ellsworth and Reich, 1993; Niinemets, 1997; Le Roux et al., 1999). The gravimetric method is convenient when LAI has to be estimated from very large leaf samples.

3. Indirect LAI determination

Indirect methods, in which leaf area is inferred from observations of another variable, are generally faster, amendable to automation, and thereby allow for a larger spatial sample to be obtained. For reasons of convenience when compared to the direct methods, they are becoming more and more important. Indirect methods of estimating LAI in situ can be divided in two categories: (1) indirect contact LAI measurements; and (2) indirect non-contact measurements. These are ground-based measurements that usually integrate over one single stand only.

Air- and space-borne methods on the other hand are applied for LAI determination on forest or landscape level. These methods are based on differences in spectral reflection between vegetation and other coverage (e.g. Ripple et al., 1991; Wulder et al., 1998). The description of these techniques however falls out of the scope of this paper.

3.1. Indirect contact LAI measurement methods

3.1.1. Inclined point quadrat

This method was developed by Wilson (1960, 1963) and consists of piercing a vegetation canopy with a long thin needle (point quadrat) under known elevation (i.e. the angle between the needle and the horizontal plane when vertically projected) and azimuth angles (i.e. the bearing of the needle from north when horizontally projected) and counting the number of hits or contacts of the point quadrat with "green" canopy elements. It is the elevation angle that determines the impact of the canopy structure on the number of hits.

The determination of LAI of the vegetation by means of this method is then possible using rather simple equations based on a radiation penetration model. When the method is restricted to one single canopy piercing, an elevation angle β of 32.5° is preferable. At that elevation angle, the extinction coefficient K of a leaf population with random azimuth distribution in the canopy is more or less constant ($K = 0.9$) at the different leaf angles α and, under assumption of azimuthal symmetry, leaf area index, L, can be estimated as follows (Lemeur, 1973):

$$L = 1.1\, N(32.5) \quad (1)$$

where N (32.5) is the number of contacts with an elevation angle α of 32.5°.

Better LAI estimations are possible when the needle is repeatedly dropped in the vegetation canopy under varying elevation angles. The general formula then becomes:

$$N_i = LK_i \tag{2}$$

where N_i is the number of contacts of the needle, dropped with elevation i, with the vegetation and K_i the extinction coefficient with elevation i. The crucial element of this method is the ability to assess the number of contacts between the needle and the vegetation canopy without disturbing the latter.

The method is attractive because the assumption of random leaf distribution is not necessary and because of its non-destructive character. Bonhomme et al. (1974) applied this technique and compared it to gap fraction measurements by hemispherical photography and a very good agreement was found between the actual and estimated LAI values for young crops.

The principal disadvantage of the method is the requirement for a large numbers of insertions (typically at least 1000) in order to obtain a reliable assessment, resulting in a lot of fieldwork. Moreover, this technique is difficult to implement in vegetation types with canopies higher than 1.5 m (such as forests), because of the required physical length of the needle(s). In order to overcome these technical limitations, significant modifications have been proposed, e.g. using a laser ray instead of a needle as the point quadrat (Vanderbilt et al., 1979), or implementing an automated contact detection system based on a fibre optics probe (Caldwell et al., 1983), or using only a vertically-dropped plumb bob (Miller and Lin, 1985).

3.1.2. *Allometric techniques for forests*

Allometric techniques rely on relationships between leaf area as such and any dimension(s) of the woody plant element carrying the green leaf biomass, i.e. stem diameter, tree height, crown base height etc. Allometric relations between the leaf area determined via destructive sampling and the basal area of the physiologically active sapwood area have been proposed. Such sapwood-to-leaf-area conversions are based on the pipe model theory that stems and branches are considered an assemblage of pipes supporting a given amount of foliage. The highest correlation coefficients were found between sapwood area and leaf area (Gower and Norman, 1991; Smith et al., 1991), very high correlation coefficients between stem basal area and leaf area (e.g. Bartelink, 1997), and between diameter-at-breast-height (DBH) and leaf area (e.g. Le Dantec et al., 2000) of trees in the same stand.

Physiologically, the amount of foliage that can be supported by sapwood decreases as trees approach maximum height, likely because of hydraulic limitations to water transport in tall trees that lead to cavitation of vessels (Ryan et al., 2000). Whitehead et al. (1984) documented a linear relation between leaf area and the product of sapwood area and sapwood permeability, supporting the hypothesis that the relation between leaf area and sapwood area is governed by the permeability. They found that sapwood area, sapwood permeability, and the product of these two variables decreased with depth through the crown of the trees. As a consequence, the assumption of constant sapwood permeability and sapwood fraction with height must be rejected for large trees, and the use of sapwood area or DBH to predict LAI may result in considerable LAI overestimation. The literature also reveals that leaf area calculated from non-site-specific sapwood allometrics tends to overestimate LAI when compared to indirect optical estimates (see Section 4) even when corrected for clumping and for the interception of light by stems and branches (e.g. Law et al., 2001). They are nevertheless suggested to be more appropriate than optical gap fraction-based measurements, for stands with high leaf area, because these optical measurements saturate at LAI values of about 5 (Gower et al., 1999). However, the trade-off is that the use of such allometric equations is restricted because of their site-specificity, as sapwood area/leaf area relationships have been shown to be stand-specific and dependent on season, site fertility—e.g. nutrition and soil water availability—, local climate, and canopy structure—e.g. age, stand density, tree size and forest management—(Mencuccini and Grace, 1995; Le Dantec et al., 2000). In some cases, the method may not be practical, for example in areas with preservation or scientific interests where destructive sampling is prohibited. An additional problem lies in the fact that DBH is a less accurate estimator than sapwood area. Determination of the sapwood area on the other hand is a difficult process in some species due to unclear borders between sapwood and hardwood.

Computer-tomography could offer a solution; but has seldom been used in the field because of the technology involved (Raschi et al., 1995). It is a technique similar to the γ-ray probe, as it measures the attenuation of a collimated beam of radiation that traverses the trunk, and it allows the density of different parts of a trunk section to be mapped by scanning the trunk in several directions. The alternative use of pressler cores is possibly inaccurate due to the possibly non-circular distribution of sapwood and hardwood in the stem. Finally, wood permeability is not commonly measured (Law et al., 2001).

3.2. Indirect non-contact LAI measurement methods

Optical methods are indirect non-contact methods and are more commonly implemented. They are based on the measurement of light transmission through canopies.

These methods apply the Beer–Lambert law taking into account the fact that the total amount of radiation intercepted by a canopy layer depends on incident irradiance, canopy structure and optical properties (Monsi and Saeki, 1953). It involves ground-based measurement of total, direct, and/or diffuse radiation transmittance to the forest floor, and it makes use of line quantum sensors or radiometers (Pierce and Running, 1988), laser point quadrats (Wilson, 1963), and capacitance sensors (Vickery et al., 1980). These instruments have already proven their value in the LAI estimation of coniferous (Marshall and Waring, 1986; Pierce and Running, 1988) as well as broad-leaved (Chason et al., 1991) stands. When compared to allometric methods, the approach provides more accurate LAI estimates (Smith et al., 1991). However, the light measurements required to calculate LAI necessitate cloudless skies, and generally there is the need to incorporate a light extinction coefficient that is both site- and species-specific due to leaf angle, leaf form, leaf clumping, etc. (Vose et al., 1995).

In recent years, a range of new instruments has been developed to indirectly assess in real time LAI of plant canopies. They can be divided into two main categories: a first group contains instruments that are based on *gap fraction* analysis, while a second group contains instruments based on *gap size distribution* analysis. Measuring gap fraction, some instruments permit calculating manually (luminous slat), some incorporate canopy image analysis techniques (Digital Plant Canopy Imager CI 100, MVI), while others (Accupar, Demon, Licor LAI-2000 Plant Canopy Analyzer) calculate LAI by comparing differential light measurements above and below canopy. The maximum measurable LAI is generally lower for these devices measuring gap fraction than the one assessed via direct methods, with LAI reaching an asymptotic saturation level at a value of about 5. The likely cause is gap fraction saturation as LAI approaches 5–6 (Gower et al., 1999).

To study the gap size distribution, the Tracing Radiation and Architecture of Canopies (TRAC) instrument and hemispherical photography can be used. Documented research has proven these instruments very efficient and reliable, where it concerns the measurement of LAI in forest environments (Welles, 1990). Based on error analysis, Chen (1996) stated that in coniferous stands optical methods, if combined with clumping analysis, hold the potential to provide LAI estimates that are more representative than direct estimates obtained via destructive sampling techniques.

A characteristic of the gap fraction-based approach is that it does not distinguish photosynthetically active leaf tissue from other plant elements such as stem, branches or flowers. Alternative terms for leaf area index have therefore been proposed, among them “Vegetation Area Index (VAI)” (Fassnacht et al., 1994), “Plant Area Index (PAI)” (Neumann et al., 1989), and “Foliage Area Index (FAI)” (Welles and Norman, 1991). Chen and Black (1992) used the term “effective LAI (L_e)” to describe LAI estimates derived optically. This nomenclature seems most appropriate because it recognises that conventional inversion models (see below) are incapable of measuring the surface area contributed solely by green leafy material, and that they are unable to compensate for the non-random positioning of canopy elements.

The last step in the interpretation of gap fraction for these methods in terms of LAI is based on relationships between gap fraction and canopy geometry. These relationships are derived from light extinction models, which link LAI and canopy architecture to the penetration of solar radiation through the canopy. Gap fraction, as a function of zenith angle, is the essence of such mathematical formulas and models (Norman and Campbell, 1989; Chason et al., 1991; Welles and Norman, 1991) and can be determined as follows:

$$T(\vartheta, \alpha) = \frac{P_s}{P_s + P_{ns}} \tag{3}$$

where $T(\vartheta, \alpha)$ is the gap fraction for a range of zenith angles ϑ and azimuth angles α; P_s is the fraction of sky in a region (ϑ, α) and P_{ns} is the fraction of vegetation in a region (ϑ, α).

Light extinction models describe the probability of interception of radiation within canopy layers, as well as the probability of sun flecks at the bottom of the canopy. Sun flecks correspond to gaps in the canopy when viewed along the direction of the direct solar beam. The *Poisson* model requires the assumption of random spatial distribution of the canopy, assuming that projections of leaves are randomly located in the plane of the projection (Welles, 1990). The model divides the canopy in N statistically independent horizontal layers in which leaves are uniformly and independently spread. These layers are sufficiently thin ($\Delta L = L/N$) to make the probability of having more than one contact between incoming light rays and vegetation within one layer small compared to the probability for one contact. The probability of a contact in layer ΔL:

$$G(\theta, \alpha)\frac{\Delta L}{\mu} \tag{4}$$

where $G(\theta, \alpha)$ is the mean projection of the leaf area unit in a plane perpendicular to the sunrays; and the probability of no contact is:

$$1 - G(\theta, \alpha)\frac{\Delta L}{\mu} \tag{5}$$

As N is allowed to approach infinity, the probability of a ray making exactly n contacts is described by a Poisson distribution. The gap fraction or probability for not having contact is then given by Eq. (6) (Neumann et al., 1989):

$$P_0(\vartheta) = \exp\left(-G(\theta, \alpha)\frac{L}{\mu}\right) \tag{6}$$

where $P_0(\vartheta)$ is the gap fraction at zenith angle ϑ; α the azimuth angle of leaves; $G(\theta, \alpha)$ the mean projection of the leaf area unit in a plane perpendicular to the sunrays; μ stands for $\cos\vartheta$.

However, this definition is not entirely valid for canopies with clumped leaf distributions, as is usually the case in natural systems. Canopies with clumped or more regularly distributed leaves can be described more adequately by binomial models, respectively, using negative or positive binomial probability functions (Neumann et al., 1989). Markov models (Nilson, 1971) are also appropriate. To compensate for clumping effects, Lang and Xiang (1986) proposed a combination of local linear averaging with larger-scale logarithmic-linear averaging of transmittance data. Norman and Campbell (1989), on the other hand, indicated that for isolated canopies in open tree stands, the inversion kernel might be more complicated than the one defined by Eq. (6). All models, however, require some information on the distribution of leaf angles and leaf azimuths within the canopy, with the binomial and Markov models also necessitating an additional parameter to describe the canopy orderliness. Given these inputs plus the solar elevation, the models then estimate the solar radiation regime within the canopy if LAI is given, or they invert the procedure and compute the LAI from the radiation regime (e.g. the sun fleck probability). It is evident that with all input parameters available, LAI may be derived from the inversion of Eq. (6).

With respect to the practical application, it has been shown that most instruments based on gap fraction assess the effective LAI under the assumption of random spatial distribution of leaves (Dufrêne and Bréda, 1995). It is, however, primarily foliage clustering at the shoot level that invalidates this assumption, resulting in an underestimation of LAI (Nackaerts et al., 1999). The discussion about clumping and the effect on the effective LAI is described in Weiss et al., this issue.

Gap fraction and gap size data can be assessed in different ways. The instrumentarium will now be described.

3.2.1. DEMON

The DEMON (CSIRO, Canberra, Australia) is an instrument for measuring the direct solar beam transmission. It measures above and below canopy light intensity and uses software to calculate LAI. A detector is held parallel to the sun's direct beam to intercept the rays passing through the canopy of interest (below canopy) or those unobstructed from the sun (above canopy). Filters are used to limit the spectrum of received light to a band near 430 nm, thus minimising the effects of scattering by the foliage (Welles, 1990).

Gap fraction is computed using a linear average of the transmittance. The DEMON has on-board processing for computing and storing log-averaged gap fractions for a large number of transects. LAI is calculated later out of the data by model inversion and means of special averaging techniques (Dufrêne and Bréda, 1995). Requirements for it's correct use are unobscured sun, and a range of sun angles. The main disadvantage of the DEMON system is that it is time-consuming, since data have to be collected three times per day at least, in order to cover a sufficient range of sun inclinations. This may be a limiting factor in certain climates (cloudiness) and at high latitudes in winter (too narrow range of sun angles) (Welles, 1990). The DEMON is designed for forest settings, but the operator must be able to walk steadily along the forest floor keeping the sensor aimed at the sun, so under storey and litter is a potential problem.

3.2.2. Ceptometer

The Sunfleck Ceptometer (Decagon Devices Inc., Pullman, WA, US) was a first model of line quantum sensor making use of 80 individual sensors on a probe and a control unit, which combines the different sensors and represent them on a screen. It strictly measures the sun fleck fraction or the quantity of PAR-radiation by means of the probe under a canopy and in an open field. A threshold value can be selected, and the fraction of the detectors that are reading above that amount is computed. Thus, gap fraction can be read directly, without the need for above canopy readings or shading devices. LAI calculations have to be performed manually though. Accupar-80 (Decagon Devices Inc., Pullman, WA, USA) is a newer version of the ceptometer and takes into account the canopy's leaf distribution. Moreover, it is able to make LAI calculation an instant measurement. Another important advantage with respect to the Sunfleck ceptometer is the ability to partition the probe to read in segments.

The most important problem with the radiation measurements is the large variability between the measurements. For that reason, it is necessary to make enough measurements in order to get a reliable and representative result. Moreover, this technique is not suitable in coniferous forests, due to penumbral effects in the sun fleck fraction. This means that the sun flecks on the forest soil consist of an area in full sun that moves over into full shadow (umbra) at the edges. In between these two extremes, there is a penumbral zone where the gradual transition occurs from sun to shadow, which makes the subjective choice of the threshold value crucial for the result.

3.2.3. LAI-2000 canopy analyser

The LAI-2000 (Licor Inc., Nebraska) is a portable instrument that does not require additional data acquisition and processing, but it is able to provide immediate LAI estimates, measuring simultaneously diffuse radiation by means of a fisheye light sensor in five distinct angular bands, with central zenith angle of 7, 23, 38, 53 and 68°. The light level is measured in clearings without trees and below the canopy. Moreover, there is an in-built optical filter that rejects incoming radiation with wavelengths above 490 nm in order to minimise the radiation scattered by the canopy. Thereby, a maximum contrast between leaf and sky is achieved. The ratio of the two values gives the transmittance simultaneously for each sky sector. LAI is then estimated by inversion of the Poisson model comparing the transmittances.

The calculations, which are automatically derived by the internal software, are based on four assumptions: (1) foliage is an optically black body that absorbs all the light it receives; (2) light blocking plant elements are randomly distributed in the canopy; (3) plant elements have the same projection as simple geometrical convex shapes; and (4) plant elements are small compared to the area spanned by each ring.

Assuming that the gap fraction, being the proportion between the below and above canopy measurement of the LAI-2000, is equal to the mean light transmission $T(\vartheta)$, Eq. (1) can be rewritten as follows (LI-COR, 1992):

$$G(\vartheta)L = -\cos(\vartheta)\ln[T(\vartheta)] = K(\vartheta) \quad (7)$$

where $K(\vartheta)$ is the contact frequency and $T(\vartheta)$ is the mean light transmission.

The contact frequency is the number of contacts made when a virtual needle is inserted through the canopy under an inclination angle equal to ϑ (Lang, 1987). The LAI-2000 calculates a numerical solution for Eq. (7) for all five detector's view angles from the registered transmission data (Welles and Norman, 1991):

$$L = -2\sum_{i} \ln[T_i]\cos\vartheta_i W_i \quad (8)$$

where i is 1–5, and W_i are the weighting factors related to each element of the sensor. These are respectively 0.034, 0.104, 0.160, 0.218 and 0.484.

The LAI-2000 is also capable of doing all computations on-board, and stores measurements and results. It has been used with success to estimate LAI in continuous and homogeneous canopies, such as millet and grasslands, validated by direct estimates of LAI based on harvesting (Levy and Jarvis, 1999). In discontinuous and heterogeneous canopies, the potential of this instrument is restricted by a general tendency towards underestimating LAI (Chason et al., 1991; Dufrêne and Bréda, 1995). Until now, the underestimation errors caused by clumping could not be satisfactorily addressed including correction factors or adapting radiation models. Adapted models such as the Markov model or the negative binomial model are not compatible with the data measured by the LAI-2000 and are not in an operational form (e.g. Chason et al., 1991).

Impact of external factors (illumination conditions and boundary effects) can be minimised by means of a 270° view cap (Nackaerts and Coppin, 2000). A potential practical weakness of the LAI-2000 approach is the requirement for an above canopy reference reading in order to get an accurate LAI estimation (Welles, 1990). A disadvantage is that it captures the forest canopy with only a coarse resolution of five concentric rings using immediate integration procedures, so making a posteriori detailed spatial analyses (i.e. foliage distribution) impossible.

3.2.4. TRAC

The Tracing Radiation and Architecture of Canopies (TRAC) instrument (3rd Wave Engineering, Ontario, Canada) accounts not only for canopy gap fraction but also canopy gap size distribution (the physical dimensions of a gap). The canopy gap size distribution or clumping index quantifies the effects of non-random spatial distribution of foliage that often occurs in mixed-stands with broad-leaved and conifer species. It is hand-carried by a person walking at a steady pace. Using the solar beam as a probe, it records by means of three photosensitive sensors the transmitted direct light at high frequency. The TRAC technology has been validated in several studies (Chen et al., 1997; Kucharik et al., 1997). The clumping index obtained from TRAC can be used to convert LAI_{eff} to LAI. When TRAC is used for at least half a clear day, an accurate LAI value for a stand can also be obtained using TRAC alone. It is recommended (Chen et al., 1997) that TRAC be used to investigate the foliage spatial distribution pattern, while LAI-2000 is useful to study foliage angular distribution pattern. So the combination of TRAC and LAI-2000 allows quick and accurate LAI assessment of a canopy.

The TRAC quantifies the clumping effect by measuring the canopy gap size distribution. For deciduous stands the clumping index measured from TRAC includes the clumping effect at all scales, but conifer stands it only resolves the clumping effect at scales larger than the shoot (the basic collection of needles). The instrument is unable to account for within shoot clumping in conifers because small gaps (less than a few millimetres in some cases) between needles disappear in shadows within the sun fleck gap-size distribution projected onto the ground (Miller and Norman, 1971). Chen et al. (1997) have recommended integrating the effective LAI measurement at several zenith angles of LAI-2000, with the clumping index (gap size) of the TRAC, to produce a more accurate estimate of LAI that accounts for both gap fraction and gap size distribution.

3.2.5. Hemispherical canopy photography

3.2.5.1. Basics/image characteristics. Hemispherical canopy photography is a technique for studying plant canopies via photographs acquired through a hemispherical (fisheye) lens from beneath the canopy (oriented towards zenith) or placed above the canopy looking downward. A hemispherical photograph provides a permanent record and is therefore a valuable information source for position, size, density, and distribution of canopy gaps. It is able to capture the species-, site- and age-related differences in canopy architecture, based on light attenuation and contrast between features within the photo (sky versus canopy). Hemispherical photographs generally provide an extreme angle of view, generally with a 180° field of view. In essence hemispherical photographs produce a projection of a hemisphere on a plane (Rich, 1990). The exact nature of the projection varies according to the used lens. The simplest and most common hemispherical lens geometry is known as the polar or equi-angular projection (Herbert, 1986; Frazer et al., 1997). In a perfect equi-angular pro-

Fig. 1. Hemispherical image.

jection of a 180° field of view, the resulting circular image (Fig. 1) shows a complete view of all sky directions, with the zenith in the centre of the image and the horizons at the edges.

3.2.5.2. Imaging devices and image processing. Various authors (e.g. Bonhomme and Chartier, 1972; Bonhomme et al., 1974; Anderson, 1981; Chan et al., 1986; Wang and Miller, 1987) have analysed hemispherical photographs to obtain LAI, often using some form of automated scanning of photographs. They invariably inverted a Poisson model to obtain LAI estimates. Mussche et al. (2001) concluded after a comparative study that the exponential model for light extinction was not appropriate and created an underestimation of LAI, which could be avoided using another light extinction model (e.g. negative binomial model). Moreover they suggested that underestimation of LAI by hemispherical photographs could also partially be due to the exposure and development of the film.

With the advent of affordable digital technologies, standard graphic image formats, and more powerful desktop computing, digital image analysis techniques have been used increasingly to examine hemispherical canopy photographs (Rich, 1988, 1989; ter Steege, 1993; Canham, 1995). In that context, analysis of hemispherical photographs has been successfully used in a diverse range of studies to characterise plant canopy structure and light penetration, as has been investigated by several researchers (Canham et al., 1990; Rich et al., 1993; Easter and Spies, 1994).

When traditional analogue hemispherical photography is used to determine LAI, apart from the time-consuming processing, difficulties in distinguishing sunlit leaves from relative small and underexposed gaps in the canopy arises. As such, camera exposure settings have a major impact on the LAI measurements and are a major cause of measurements errors as demonstrated by Chen et al. (1991).

Today, however, digital cameras offer forest scientists a practical alternative to overcome some of these technical problems, mainly those concerning the development of the traditional film photography (Frazer et al., 2001b). Digital cameras are available now with a very large number of pixels that provides a spatial resolution close to that of classical photographic films (Hale and Edwards, 2002). In comparison to analogue cameras, these digital sensors have better radiometric image quality (linear response, greater dynamic range, wider spectral sensitivity range (King et al., 1994) and offer some practical advantages: (1) digital images make the expense and time associated with photographic film, film development, and scanning unnecessary and thereby eliminate errors that may occur during this procedure; (2) the potential of real time processing and assessment in the field; and finally (3) the unlimited image treatment possibilities.

One of the main problems cited in the literature of hemispherical photography for determination of LAI is the selection of the optimal brightness threshold in order to distinguish leaf area from sky area thus producing a binary image. A series of software packages for hemispherical images processing have been developed (e.g. Becker et al., 1989; Baret et al., 1993; Nackaerts, 2002), Hemiview (Delta-T Device), SCANOPY (Regent, Rich et al., 1993), GLA (Forest Renewal BC, Frazer S., 1999) and EYE-CAN (Weiss, 2002). Previous research demonstrated that with a high resolution digital camera, the choice of the threshold level would be less critical, because the frequency of mixed pixels is reduced in comparison to the aggregation of pixels in cameras with lower resolution (Blennow, 1995).

3.2.5.3. Sources of error. As with any remote sensing technique, errors can occur at any stage of image acquisition or analysis. Methodological errors often occurring have been discussed by Olsson et al. (1982) and Rich et al. (1993) (Table 1). Strict protocols should be developed to prevent problems from compounded errors.

Table 1
Levels at which errors can be introduced in digital hemispherical canopy photography (Rich, 1988)

Image acquisition	
	Camera positioning
	Horizontal/vertical position
	Exposure
	Evenness of sky lighting
	Evenness of foliage lighting (reflections): direct sunlight
	Optical distortion
Image analysis	
	Distinguishing foliage from canopy openings
	Assumed direct sunlight distribution
	Assumed diffuse skylight distribution
	Assumed surface of interception
	Image editing/enhancement
	Consideration of missing areas
Violation of model assumptions	
	Assessment of G-function variations
	Leaf angle variability
	Consideration of clumping

3.2.6. *Hybrid method*

The Multiband Vegetation Imager (MVI) is a new optical instrument that uses a filter exchange mechanism mounted on a 16-bit CCD camera to capture two-band, (VIS, 400–620 nm and NIR, 720–950 nm) image pairs of plant canopies from the ground looking upward. Due to these two wavelength bands, the MVI has the unique ability to separate the various scene components (green and non-green vegetation elements as well as sunlit and shaded fractions) in a canopy. The capability to capture high-resolution NIR images of canopy structure separates the MVI from other optical instruments, such as the DEMON and LAI-2000 (Welles and Cohen, 1996). Calculation of LAI is based on gap fraction inversion. It is used to study the spatial relationship of woody and non-woody foliage in boreal forest canopies, and estimate the percentage of effective branch area index that is not preferentially shaded by other foliage in typical boreal forest crowns. The instrument can correct indirect LAI measurements for non-random distributions of leaves or shoots and branches, and for the fraction of the branches and stems that intercepts light with respect to indirect LAI measurements with LAI-2000. Kucharik et al. (1998) showed that indirect LAI values adjusted with the MVI can approximate the direct LAI measured with destructive sampling to within 5% in Aspen. However, one drawback of multiband cameras outlined by Frazer et al. (2001b) is the colour blurring towards the edge of the field of view due to chromatic aberration and colour registration that may degrade the effective spatial resolution.

3.2.7. *Comparison of instruments*

Table 2 shows the characteristics associated with the different devices described above. Most of the studies dealing with instrument comparisons have focused on forests. Conclusions driven by Chason et al. (1991) show that DEMON and LAI-2000 give satisfactory results for *LAI* estimation, although the DEMON instrument is less practical (one LAI-2000 measurement corresponds to multiple DEMON acquisitions during half a day). Conversely, Martens et al. (1993), investigating a coniferous forest and a deciduous orchard, found low values of absolute correlation coefficients between the LAI derived from LAI-2000 and Accupar-80. However, better consistency was observed between LAI-2000 and hemispherical cameras. Chen et al. (1997) made a comparison of four instruments and recommend the use of LAI-2000 or hemispherical cameras for effective LAI evaluation in coniferous forests. They noted that for hemispherical cameras, the binarisation threshold between vegetative and non-vegetative elements must be accurately adjusted. Also Planchais and Pontailler (1999) compared LAI-2000 with hemispherical photographs in beech stands and showed that both indirect techniques gave the same estimation of gap fraction at all zenith angles. However, in studies requiring fine details of the canopy structure (e.g. determining the foliage angular distributions) or the light penetration (e.g. measuring of bi-directional gap fraction), the advantage of spatial discrimination of hemispherical photographs has been proven useful (Andrieu et al., 1994; Nilson and Ross, 1979; Chen et al., 1991). In the case of crops (maize and white beans), Pacheco et al. (2001) have shown that LAI-2000 was more accurate for effective LAI estimation than the TRAC device. However, the concurrent use of LAI-2000 or hemispherical cameras and TRAC devices allows the evaluation of the clumping parameter. Chen and Cihlar (1995) and Law et al. (2001) noticed that it is more difficult to estimate clumping (and therefore the true LAI) for high and dense canopies due to darkness and multiple

Table 2
Comparison between instruments allowing indirect LAI measurements

System	Illumination conditions	Spectral domain	No. of zenith angles	Azimuthal coverage	Gap size distribution	Reference readings	Post-processing	Computer resources
DEMON	Direct	430 nm	–	–	No	Yes	No	Low
Sunfleck ceptometer	Diffuse, direct	PAR	–	–	Yes	Yes	Yes	Low
AccuPAR	Diffuse, direct	PAR	–	–	Yes	Yes	No	Low
LAI-2000	Diffuse	<490 nm	5	Full range selectable by hardware	No	Yes	No	Low
Tracing Radiation and Architecture of Canopies (TRAC)	Direct	PAR	–	–	Yes	Yes	No	Low
Hemispherical Cameras	Diffuse, direct	Selectable	Full range	Full range selectable by software	Yes	No	Yes	High
Multiband Vegetation Imager (MVI)	Diffuse	VIS and NIR	Full range	Full range	Yes	No	Yes	High
Ideal device	Diffuse and direct	VIS and NIR	Full range	Full range selectable by software	Yes	No	–	–

scattering inside the canopy. McPherson and Peper (1998) showed on single urban trees that processing non-hemispherical photographs of the tree provide the best LAI estimates when compared to LAI-2000 and ceptometer. However, they observe a systematic underestimation bias for all the methods probably due to clumping. Compared to destructive sampling, the log-average method of van Gardingen et al. (1999) for hemispherical photography was shown, to significantly reduce the underestimation of leaf area index obtained from analysis of clumped canopies. Conventional analysis of hemispherical photographs resulted in an underestimate of 50% compared to the destructive harvest, while the segmented analysis reduced this to 15%. White et al. (2000) concluded that hemispherical photography is the most accurate and efficient way, as compared to LAI-2000, Accupar-80 or a laser altimeter for long term monitoring of arid ecosystems. This was in good agreement with the recent results of Leblanc et al. (2002), who concluded that hemispherical photographs in a grid offer a good potential to replace LAI-2000 and TRAC devices for canopy structure measurement. Englund et al. (2000) evaluated the difference between digital and film hemispherical photography in measuring forest light environments and concluded that digital photography was effective and more convenient and inexpensive than film cameras, but they recommended caution when comparisons are made between the two techniques. Frazer et al. (2001a) investigated both types of cameras for analysis of forest canopy gap structure and light transmission and found out that digital and film measures were correlated better under more open canopies as well as under overcast sky conditions.

As a conclusion on the gap fraction measurement devices, it appears that hemispherical cameras offer the greatest potential, if high spatial resolution and large signal dynamics of well registered visible and NIR bands are available.

4. Conclusions

Indirect determination of LAI, as an important measure of canopy structure, is affected by clumping of needles in conifer species and to a lesser extent of leaves in deciduous species. Clumping seems to be the main factor causing errors in the LAI estimation. This review demonstrates that all methods have specific problems and limitations, the decision as to which method to use depends on many factors such as: the required accuracy, the measurement time period, the research scale, the available budget, etc. Moreover, the usefulness of new instruments, e.g. MVI needs to be tested and investigated more extensively.

As a conclusion of the review, the characteristics of an ideal device for measuring LAI, have been added to Table 2. It should be a hemispherical sensor in order to simultaneously measure the canopy gap fraction at a range of zenith angles, enabling more efficient sampling than is possible with linear sensors (Welles and Norman, 1991). It should permit derivation of the gap fraction distribution as a function of the zenith angle to get information on leaf clumping. It should have predefined exposure, and ability to detect green and non-green elements. Further, it should permit acquisition of data over low vegetation by looking downward. It should also provide a visualisation of the canopy, which can help identify possible measurements problems. In addition to the estimation of the leaf area index, such an ideal hemispherical device could also be used to characterise directly the light climate within canopies. Obviously, hemispherical cameras have these potential features.

Hemispherical photography, a technique that is markedly cheaper than alternatives, has already proven to be a powerful indirect method for measuring various components of canopy structure and under story light regime. Numerous advances in hemispherical analysis, which have taken place over the last decade, are directly related to evolving computer, photographic, and digital technologies and scientific modelling methods. Hemispherical photographs can be archived, reprocessed when improved models become available and used to perform other measurements, for example, fractal dimension, architecture and light regime below the canopy (Beaudet and Messier, 2002).

Further testing and defining of a standardised field protocol for digital hemispherical photography is however needed to improve this technique and to achieve the standards of an ideal device:

- The segmentation between the green and non-green vegetation versus the background (sky or soil) should be improved as compared to the performances of current hemispherical camera systems.

1. A proper selection of the spectral bands used could help increasing the contrast between these elements. The use of the red and IR bands, like in the MVI instrument (Kucharik et al., 1997), appears quite appealing.
2. A high dynamic range (12-bit) is required in order to get similar discrimination performances for the shadowed and illuminated elements. This will allow taking measurements both under direct and diffuse conditions. The possible use of non-linear response sensors could probably provide a good technical solution to this problem.
3. The image resolution is critical to avoid mixed pixels and thus misclassification. This could be achieved by using larger matrices sensors that are now becoming available. This could be achieved also by limiting the field of view of the lens to values in the range 0–60° or 75°. As a matter of fact, for higher zenith angles, the elements are quite far away from the sensor as compared to nadir viewing, and the gaps are therefore very small posing important problems for classification. In addition, explicit accounting for the mixed pixels as proposed by Leblanc et al. (2002) could also improve the classification performances.
4. The simple binarisation thresholds currently applied on brightness levels or colour indices should be replaced by more efficient and robust classification techniques.
5. The influence of exposure settings (shutter speed and lens aperture) has shown to be important for the thresholding step. In general, 1–2 stops of overexposure relative to the automatic exposure metered outside the canopy are recommended. Further investigation is however needed to achieve standards.

- Image processing

The main weakness of methods based on hemispherical photography is due to the post processing step which is generally tedious and time consuming since each image is processed independently from the others; although images are generally taken as a series to characterise a particular canopy and accounting for the spatial heterogeneity. Consequently, development of software is required to process a series of images and reduce the intervention of the operator.

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