Methods for Leaf Area Index Determination
Part I: Theories, Techniques and Instruments

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Abstract

Rapid, reliable and objective estimations of Leaf Area Index (LAI) are essential for numerous studies of the atmosphere, as LAI is very often a critical parameter in process-based models of vegetation canopy response to global environmental change. This paper compiles current knowledge concerning the use of direct and indirect methods for LAI determination. The emphasis will be on techniques, theories and instruments. The value of optical LAI measurements via hemispherical photography has already been demonstrated in previous studies. We suggest that the use of a digital camera with high dynamic range has the potential to overcome a number of described technical problems about hemispherical photography.

Keywords: Leaf Area Index/ Gap fraction/Hemispherical photography/ Digital camera

1. Introduction

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 broadleaved trees with flat leaves, this definition is usable 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 *maximal* 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 coefficients of several convex and concave objects of different angular distributions, Lang (1991) and Chen and Black (1992) suggested that half the total interception (non-projected) 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.

The LAI of vegetation depends on species composition, development stage, and seasonality. Furthermore the LAI is strongly dependent on the prevailing site conditions and the management practices. 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 Quercus petraea (Matus) Liebl. (Le Dantec *et al.*, 2000) to 14 for 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 (Ni *et al.* 2001) have been published. We suspect that these may result from inappropriate simplifications in the measurement method within of these large-scale studies.

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, 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 precise, but they have the disadvantage of being extremely time-consuming and as a consequence making large-scale implementation only marginally feasible. Precision problems may in this case result from the definition of LAI, the scaling-up method, or from the error accumulation due to frequently repeated measurements.

2.1. Harvesting and non-harvesting methods

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).

Destructive sampling of a part 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.

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 3 or 5 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. It has 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 tree is very labour-intensive (Schauvliege, 1995). 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 of a predetermined size are hereby placed at any position in the stand, so that a higher litter trap frequency will result in an improved accuracy as the effect of up-scaling (under the assumption of lateral homogeneity of the forest canopy) becomes less prevalent. Under the appropriate spatial and temporal sampling schemes, litter traps have proven very useful in deciduous forests (Neumann *et al.*, 1989). 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 yearly biomass accumulation, 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, it is the integrated measure for LAI over the measurement period that is provided, so it is 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 change their leaves during growing season, as for example poplars, litter trap data would be an overestimation of the maximal LAI. Moreover, the method does not obtain 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 its origin remains however a problem. This statistical condition can only be met by incorporating a high number of litter traps per area unit. There seems furthermore no to exists a consensus yet on the spatial distribution 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).

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 perimeter can be measured with a planimeter, and its area can be computed from this perimeter assessment. There are different planimeter types on the market for this purpose. A first type is the scanning planimeter (e.g. Li-3000, Licor, Nebraska) 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, Nebraska) 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-201 (Delta-T devices, Cambridge) 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 Ci-251 conveyer image analyser (Delta-T devices, Cambridge) has a very high spatial resolution and is 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. An example is the 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 about 75-105°C until a constant weight is reached. 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 subsample LMA. In order to get a homogeneous distribution of sun- and shade leaves; it has proven of crucial importance to mix the entire field litter trap harvest properly prior to extracting the subsample for LMA. Furthermore, attention must be paid to the large spatial and temporal variations in LMA values that have been shown to occur with 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 out of very large leaf samples.

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).

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.

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 â 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 á and, under assumption of azimuthal symmetry, LAI can be estimated as follows (Lemeur, 1973):

$$LAI = 1.1 \times N(32.5) \qquad (1)$$

where

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

$$N_i = LAI \times K_i \qquad (2)$$

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 using the gap fraction measurements and found a very good agreement 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 fiber optics probe (Caldwell *et al.*, 1983), or using only a vertically-dropped plumb bob (Miller and Lin, 1985).

3.1.2. Allometric techniques

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. Very high correlation coefficients were found between sapwood area and leaf area (Gower and Norman, 1991; Smith *et al.*, 1991), 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 permeability, supporting the hypothesis that the relation between leaf area and sapwood area is governed by the permeability. They found that sapwood area, permeability, and the product of these two variables decreased with depth through the crown of the trees. As a consequence, the assumption of constant 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 4.) even when corrected for clumping and wood interception (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). An additional problem lies in the fact that sapwood determination is a difficult process in some species due to unclear borders between sapwood and hardwood. In some cases, the method may not be practical, for example in areas with preservation or scientific interests where cutting is prohibited. Computer-tomography could offer a solution but field application is far from operational as yet. The alternative use of pressler cores is possibly inaccurate due to the eventually 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.

One approach applies 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 broadleaved (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 instruments has been developed to indirectly assess in real time LAI of plant canopies. They can be divided in two main categories: a first group contains instruments that are based on *gap fraction* analysis, while in a second group instruments based on *gap size distribution* analysis can be classed. Some instruments allow calculating gap fraction 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 in a rather simple way by comparing differential light measurements above and below canopy. The maximal 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).

TRAC and hemispherical photography study the gap size distribution. 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 accurate 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 recognizes 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:

$$T(J,a) = P_s / (P_s + P_{ns}) \qquad (3)$$

where $T(J,a)$ is the gap fraction for a region with zenith angle J and azimuth angle a *;* Ps is the number of pixels sky in a region (J,a) and P_{ns} is the number of pixels vegetation in a region (J,a).

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 assumption of random spatial distribution of the canopy requires a *Poisson* model, assuming that projections of leaves are randomly located in the plane of the projection (Welles, 1990). The Poisson model divides the canopy in N statistically independent horizontal layers in which leaves are uniformly and independently spread. These layers are sufficiently thin (ÄL = LAI/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 contac

$$G(q,a) * \text{ÄL/î} \qquad (4)$$

and the probability of no contact is:

$$1 - G(q,a) * \text{ÄL/î} \qquad (5)$$

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 Equation (6) (Neumann *et al.*, 1989):

$$P_0(J) = \exp\left(-G(q,a)* LAI / m\right) \qquad (6)$$

where $P_0(J)$ as the gap fraction at zenith angle J; a the azimuth angle of leaves; $G(q,a)$ the mean projection of the leaf area unit in a plane perpendicular to the sunrays; ì stands for $\cos J$.

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 may 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 by 30% to 70% (Stenberg, 1996; Nackaerts *et al.,* 1999). It must be said, though, that the phenomenon is less prevalent in broadleaved canopies than in coniferous ones (Chen *et al.*, 1997). The occurrence of clumping is not restricted to the shoot level, however, but may also take place at branch and crown level (Chen and Cihlar, 1996).

Various experimental studies already recognized the problem of non-randomness, suggesting correction factors account for clustering or clumping when measuring LAI via optical methods (Gower and Norman, 1991; Chen and Black, 1992; Fassnacht *et al.*, 1994; Chen, 1996). The limitation of the proposed correction factors is that they are not universally applicable (Deblonde *et al.*, 1994, Stenberg, 1996), and that they are usually very costly to come by, involving additional intensive sampling procedures and requiring new instrumentation such as, for example, the TRAC instrument (Chen and Cihlar, 1995). TRAC measures gap-size distribution and is thus able to determine clumping. Moreover, in case of the introduction of clustering indices or clumping factors, it is the effective foliage area index that is determined instead of the real foliage area. Fractal dimension, which quantifies the deviation from a random needle distribution, is tested recently as a correction factor for needle clumping with LAI 2000 measurements (Nackaerts *et al.,* 2002). Unlike other parameters described in the literature that are highly tree species and site-specific, fractal dimension can be easily determined in situ with each LAI measurement. It therefore has the potential to offer an universal solution for correction of LAI measurements.

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 minimizing 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 a 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 the 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 understorey and litter is a potential problem.

3.2.2. Ceptometer

The Sunfleck Ceptometer (Decagon Device, Pullman, WA, US) was a first model of line quantum sensor making use of 40 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 Device, Pullman, WA, US) is a newer model and uses the same principle for 80 photodiodes. It takes into account the canopy’s leaf distribution and is able to make LAI calculation an instant measurement. Another important advantage is that the Accupar-80 has 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 in 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 Analyzer

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 degrees. 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 below 490nm in order to minimize 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(J), Eq. (1) can be rewritten as follows (LI-COR, 1992):

$$G(J) \times LAI = -\cos(J) x \ln[T(J) = K(J) \quad (7)$$

where $K(J)$ is the contact frequency and $T(J)$ 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 J (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):

$$LAI = 2\sum_i - \ln(T_i)\cos J_i W_i \qquad (8)$$

where i is 1 to 5, and W_i are the weight factors related with the relative of 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 harvests (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). Uptil now, the underestimation errors caused by clumping could not satisfactorily be adressed 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 under operational form (e.g. Chason *et al.*, 1991).

Impact of external factors (illumination conditions and boundary effects) can be minimized 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 only in the 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 broadleaved- and conifer species. It is hand-carried by a person walking on 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 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 combined use 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 millimeters 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 for downward looking. Therefore it can be used for any canopy type (Rich, 1990). Furthermore, the use of fish-eye lens allows the gap fraction to be evaluated in all viewing directions, which increases the accuracy of the derived biophysical variables (LAI) and there is a potential to characterize the azimuthal distribution of the foliage and the departure to non-random leaf arrangement. In addition, it is also possible to derive estimates of the leaf area index for canopies growing on sloppy terrains.

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 vs. 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 lens that is used. Herbert (1986) mentioned four common geometrical projections used by commercially available fisheye lenses: (1) polar projection, (2) orthographic projection, (3) Lambert's equal-area projection (Schmidt-net) and (4) stereographic equal angle projection (Wulff-net). The simplest and most common hemispherical lens geometry is known as the polar or equi-angular projection (Fig. 1) (Frazer *et al.,* 1997).

[Around here Fig. 1]

The direction to all objects relative to a fixed point on the ground surface can be uniquely defined within a hemispherical object region. A polar projection assumes that the zenith angle of an object in the sky is directly proportional to the distance from the centre of the image along a radial axis (Fig. 2).

[Around here Fig.2]

This can be expressed as follows:

$$q_{obj} / 90° = r / R \qquad (9)$$

where q_{obj} is the zenith angle of an object in the hemisphere (degrees); r is the distance of the projected point from the center of the image and R is the radius of the hemispherical image (ter Steege, 1993).

In a perfect equi-angular projection of a 180° field of view, the resulting circular image (Fig. 3) shows a complete view of all sky directions, with the zenith in the center of the image and the horizons at the edges. North is conventionally towards the top of the image South towards the bottom, East towards the left and West towards the right.

[Around here Fig.3]

3.2.5.2. Imaging devices

Already in 1924, Hill designed the first hemispherical lens to study cloud cover within a hemispherical sky. Later, architects used hemispherical photos to assess so-called site-factors that estimate the solar radiation regimes at different positions within or near buildings. Forest ecologists and foresters conceived of using photographic techniques to study light environment under forest canopies. In that context, Evans and Coombe (1959) superimposed diagrams of the sun track on hemispherical photographs to study solar radiation penetration through forest canopy openings. Anderson (1964) provided the thorough theoretical basis for using hemispherical photographs for calculation of the penetration of solar beam (direct) and scattered (diffuse or indirect) components of solar radiation from visible sky directions. Others (Wang and Miller, 1987) recommended the point-drop method (Miller and Lin, 1985) as calibration for the hemispherical photographs in the calibration stands.

Various authors (e.g. Bonhomme and Chartier, 1972; Bonhomme *et al.*, 1974; Anderson, 1981; Chan *et al.*, 1986; Wang and Miller, 1987) have analyzed 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 an other 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 (e.g. film scanners, cameras, etc.), 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 characterize 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). Chen *et al.* (1997) used the methodology with success in boreal forests, whereas Dufrêne and Bréda (1995) investigated the technique in European deciduous forests. van Gardingen *et al.* (1999) and Comeau *et al.* (1998) have implemented hemispherical photography in mixed woodlands. Planchais and Pontailer (1999) compared LICOR 2000 with hemispherical photographs in beech stands and found out 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). Baret et al. (1993) have used hemispherical photographs to characterize the PAR intercepted by wheat and sugar beet canopies. Gendron et al. (1998) have demonstrated that hemispherical cameras could be used for the estimation of the photosynthetic photon flux density. Similarly, Wünsche et al. (1995) have shown that hemispherical cameras, and radiation sensors mounted on rails give comparable results those obtained by a “point-quadrat” probe for the evaluation of diffuse intercepted radiation.

van Gardingen *et al.* (1999) have improved the estimating of LAI from hemispherical images by dividing each annulus into a number of small segments. Gap fraction of each segment is calculated and the average of their logarithms is calculated for each annulus (log-average method). Comparing to destructive sampling, the log-average method was shown, to significantly reduce the underestimation of leaf area index obtained from analysis of hemispherical images 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%. Wagner (2001) concluded that LAI determination based on hemispherical photography is zenith angle dependent, so relative radiance measurements are needed.

The LAI estimated from hemispherical photographs is sensitive to photographic exposure (Chen *et al.*, 1991, Macfarlane et al., 2000), but indicated exposure may vary among cameras and light meters (Chen *et al.*, 1991; Wagner, 1998) and exposure may be metered either outside or below the canopy by different operators (Canham *et al.*, 1990; ter Steege, 1993). A shutter speed of 1/125 second or greater will generally freeze foliage movement caused by the wind. Often it is advisable to take photographs at more than one exposure for each sample position, for example “bracketing” the exposure (taken at, one F-stop above, and one F-stop below the metered reading), in order to find out the right exposure for the measurements (Chen *et al.*, 1991). The extent to which the photographs should be overexposed depends on the relative contribution of the sky and the canopy to the solid angle of the hemisphere and on the internal light meter of the camera. Exposure is the amount of light acting on the emulsion of the film and is determined by the lens aperture (f-number and shutter speed) (Grimm and Grimm, 1997). Built-in light camera meters measure the illuminance of the subject being photographed and the camera calculates ‘automatic’ exposure settings assuming the light comes from a mid-gray surface (18% visible reflectivity) by converting to photographic exposure using the expression of Unwin (1980) which is rearranged to include the film speed,

$$I = \frac{244}{F}\frac{n^2}{t} \tag{10}$$

where I is the illuminance in lux, F is the ASA rating of the film, N is the lens aperture (f number) and T is the exposure time in seconds.

A change of exposure value EV_R represents a halving or doubling of the amount light reaching the film. Therefore to make an unobscured overcast sky (18% visible reflectivity) completely white (100% visible reflectivity) should require 2.5 stops of overexposure. The complete white sky is needed in order to allow a more accurate thresholding for the binarization of the image. The new advanced cameras however have more complex light programs than Eq. 10. The digital camera Nikon Coolpix 950 (Nikon, USA) for example has three exposure metering settings: (1) *matrix metering system*: image is divided in different zones in which light is measured and an overall exposure is calculated, (2) *spot metering*: light is measured in a defined zone, (3) *center-weighted metering*: measures the light in the center and in two regions around the center. Only the spot metering allows to know the exact light exposure, whereas for example the matrix settings can not work for the fish-eye images, as the black parts of the images in that way are taken into account for exposure measurement.

Chen *et al.* (1991) investigated this influence of exposure settings (shutter speed and lens aperture) and concluded that hemispherical photography can be a more accurate method to determine LAI_{eff} in comparison with the LAI-2000, when the right exposure is achieved. They suggested 1-2 stops of overexposure relative to the automatic exposure metered outside the canopy should produce this outcome.

Furthermore, when traditional analogue hemispherical photography is used to determine LAI, a special problem apart from the time-consuming process arises, caused by the limited dynamic range. 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). Moreover, the low dynamic range causes difficulties in distinguishing sunlit leaves from relative small, underexposed gaps in the canopy.

The use of a digital camera would overcome some of these technical problems, mainly those concerning the development of the photographic film.

Traditionally, hemispherical canopy photography has relied upon conventional black and white, or color films (negatives or diapositives), and CCD-scanners to produce digital images for analysis (Frazer *et al.*, 1997). Today, however, digital cameras offer forest scientists a practical alternative to traditional film photography (Frazer *et al.*, 2001), as digital cameras are available now with a number of pixels that provides a spatial resolution close to that of classical films (Hale and Edwards, 2002). Moreover, the use of color hemispherical photographs would reduce the uncertainty associated to the green fraction that is often significant for forest canopies (Fernandes *et al*., 2002). These new devices offer some advantages: (1) digital images make the expenses 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. Also the image procession and data extraction can occur directly in the field, thus creating a more streamlined process; and finally (3) the unlimited image treatment possibilities.

3.2.5.3. Image procession

One of the main problems cited in 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 for hemispherical images processing have been developed (e.g. Becker et. al., 1989, Baret et al., 1993), Hemiview (Delta-T Device), SCANOPY (Regent, Rich et al., 1993), GLA (Forest Renewal BC, Frazer S., 1999). They are generally designed to process upward looking photographs. In this case, the brightness computed with the blue band or with the three bands is used. Recently, negative color images taken by video and digital camera were often used for the hemispherical photographs. Kato and Komiyama (2000) established a method to determine the threshold level of the brightness of a hemispherical photograph. Previous research demonstrated that with a high resolution of a 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; Berghs, 2001). In relation to analogue cameras, these digital sensors have better radiometric image quality (linear response, greater dynamic range, wider spectral sensitivity range (King *et al.*, 1994). The dynamic range is the range of discrete brightness (light intensity) levels an imaging system can distinguish. A normal photographic film generally does not provide a dynamic range of much more than 6 bits (i.e. 64 discrete brightness levels; Hinz et al., 2001). A commercial consumer-priced digital camera offers a dynamic rate of 8 bits (256 levels; e.g. Nikon Coolpix 950, Nikon, Japan). 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.* (2001) 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. Moreover, digital photographs were extremely difficult to threshold, and no single color plane seemed to improve the contrast between sky and canopy elements. He worked with an 8-bit digital camera (Nikon Coolpix 950, Nikon Inc, Japan) and the sharpness of the digital image was generally poor compared to the film. So digital imaging provides several advantages over film-based imaging: economical processing, high resolution, rapid-product turn-around, and high dynamic range, but nevertheless the intended application and use of the photographs must be carefully considered before selecting a photo system for hemispherical photography. A professional digital sensor characterized by a high dynamic range can offer 12-16 bits (e.g. Kodak DCS660, Kodak, USA). It would improve the separability between vegetation elements and sky. A leaf illuminated by direct sunlight might for example not be distinguishable from the surrounding sky on a system with a low dynamic range since the brightness difference is too small to be picked up by the imaging system.

Modern photographic film, filters, and digital image enhancement technologies offer remarkable opportunity to improve hemispherical image quality and contrast. These improvements in turn would facilitate a higher success rate in the classification of sky and non-sky pixels during the threshold process. The potential for digital image enhancement is increased using true-colour images because various combinations of techniques can be applied to any one or all of the three RGB planes. Image enhancement methods include the application of a) digital filters to mathematically recombine neighbouring pixels, b) overlays to splice multiple RGB planes or even separate images and c) tools that modify the frequency and magnitude of pixel spectra.

As a conclusion on the gap fraction measurement devices, it appears that hemispherical cameras offer the greatest potential, if a high spatial resolution, a large signal dynamics of well registered visible and NIR bands are available. White et al (2000) concluded that it 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 offer a good potential to replace LAI 2000 and TRAC devices for canopy structure measurement.

3.2.5.4. Error sources

As with any remote sensing technique, errors can occur at any stage of image acquisition or analysis. Because many steps are involved, accumulated error can become significant even though strict quality control is exercised. Methodological errors often occurring have been discussed by Olsson *et al.* (1982) and Rich *et al.* (1988) (Table 1). In order to resolve such methodological problems, the different sources of error have to be eliminated systematically. A severe error at any stage can invalidate the final results, even if other steps are without error. Strict protocols should be developed to prevent problems from compounded errors.

[Around here Table1]

On the one hand, the various photographic system components (e.g. lens, camera, exposure meter) differ from manufacturer to manufacturer with regard to their characteristics (Wagner, 1998). On the other hand, different users proceed differently in each step of their work. This has been well established for the exposure techniques used in forests and is far from being standardized (Olsson *et al.*, 1982; Chazdon and Field, 1987; Rich *et al.*, 1993).

Current hemispherical image analysis systems have kept pace with evolving digital technologies, but nevertheless there are still a number of improvements that have to be made to use the full potential of this technique. Hemispherical photography can up to now only be applied under overcast conditions in order to get a diffuse sunlight distribution, as it does not take into account the effects of local weather conditions. Moreover, above canopy reading is not necessary for the instrument, but the lack of it may lead to false threshold selection in the evaluation of hemispherical photos. Neither do they compensate for the effects of regional landform geometry and site orientation on the distribution of direct and diffuse solar radiation (Frazer, 1997). When sampling canopies over slopes, Walter and Torquebiau (2000) showed significant discrepancies between leaf area index estimated with and without slope effect correction in a boreal and a tropical rain forests. This factor should also be taken into account. The choice between downward looking and upward looking photos depends mainly on the canopy type. Upward looking photos are generally more easy to segment than downward ones. However, in the case of very dense and small canopies, upward photographs might be unfeasible or could highly disturb the canopy structure. In this case, downward looking photographs are preferred. Note that the advantage of downward looking photographs is the possibility to get a better spatial representation by increasing the distance between the camera and the canopy while keeping it not too far away to be able to get a clear image of vegetation elements, minimizing the mixed pixels problem. In the case of forests with understorey, it is therefore recommended to perform both upward (for the trees) and downward (for the understorey) photographs.

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. (2001) is the color blurring towards due to chromatic aberration and color registration that may degrade the effective spatial resolution.

3.2.7. Comparison of instruments

[Around here Table 2]

Table 2 shows the characteristics associated with the different devices described above. Most of the studies dealing with instrument comparisons are focusing 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 to use LAI 2000 or hemispherical cameras for effective *LAI* evaluation in coniferous forests. They noted that for hemispherical cameras, the binarization threshold between vegetative and non-vegetative elements must be accurately adjusted. 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 *LA*I) for high and dense canopies due to darkness and multiple 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.

The characteristics of an ideal device have been added in table 2. It should be hemispherical in order to sample the whole zenith and azimuth directions. It should allow to derive the gap fraction distribution as a function of the zenith angle to get information on leaf clumping. Obviously, hemispherical cameras have this potential features. Further, it should allow to acquire data over very low vegetation by looking downward. In addition, it provides a visualization of the canopy, which can help identify possible measurements problems. In addition to the estimation of the leaf area index, such ideal hemispherical device could be also used to characterize directly the light climate within canopies.

4. Conclusions

Leaf Area Index is an important measure of canopy structure because tree morphology, leaf orientation and distribution influence LAI estimates. Trees of different species can have therefore very different LAI values. Clumping of needles or leaves affect LAI estimation in conifer species and to a lesser extent in deciduous species and seems to be the main cause factor of errors in the LAI estimation. This review demonstrates that all methods have specific problems and limitations, the decision which method to use depends on lots of factors as there are: the accuracy needed, time period of measurements, the scale factor of the research, the budget available for the measurements, etc.

Of all the sensors available for measuring gap fraction, the LAI 2000 Canopy analyser and hemispherical photography are the most widely used. Their hemispherical sensors can 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). Hemispherical photography, a technique which is markedly cheaper than alternatives, used in the scope of indirect methods, remains a valuable alternative to other similar techniques, when sunshine is too scarce to allow work with the transmission of a direct beam and when the absence of a large clearing makes reference measurements of full sky radiation impracticable. Hemispherical canopy photography has proven to be a powerful indirect method for measuring various components of canopy structure and understory light regime. Numerous advances in hemispherical analysis have taken place over the last decade, which are directly related to evolving computer, photographic, and digital technologies and scientific modeling methods. Hemispherical photographs can be archived, reprocessed when improved models become available and used to perform other measurements, for example architecture and light regime below the canopy (Beaudet and Messier, 2002). Further testing and defining of a standardized field protocol for digital hemispherical photography is needed to improve this technique to be as operational as the TRAC and LAI 2000 are:

- ***The segmentation between the green from non- green vegetation and from the background*** (sky or soil) should be improved as compared to the performances of current hemispherical cameras systems. This could be achieved by:
  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 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 binarization thresholds currently applied on brightness levels or color indices should be replaced by more efficient and robust classification techniques.

- ***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 by series to characterize a particular canopy and accounting for the spatial heterogeneity. Consequently, it is required to develop software designed to process series of images to reduce the intervention of the operator.

Moreover the usefulness of new instruments, e.g. MVI needs to be tested and investigated more extensively.

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List of tables

IMAGE ACQUISITION

- Camera positioning
  - Horizontal/vertical position
- Exposure
- Sky lighting evenness
- Foliage lighting evenness (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

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

	Illumination conditions	Spectral Domain	N° of zenith angles	Azimuthal coverage	Gap size distribution	Reference Readings	Post- processing	Computer resources
DEMON	Direct	430nm	-	-	No	Yes	No	Low
Sunfleck ceptometer	Diffuse Direct	PAR	-	-	Yes	Yes	Yes	Low
AccuPAR	Diffuse Direct	PAR	-	-	Yes	Yes	No	Low
LAI2000	Diffuse	<490 nm	5	Full range Selectable by hardware	No	Yes	No	Low
TRAC	Direct	PAR	-	-	Yes	Yes	No	Low
Hemispherical Cameras	Diffuse, (Direct)	Selectable	Full range	Full range selectable by software	Yes	No	Yes	High
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	-	-

Table 2. *Comparison between instruments allowing indirect LAI measurements.*

List of figures

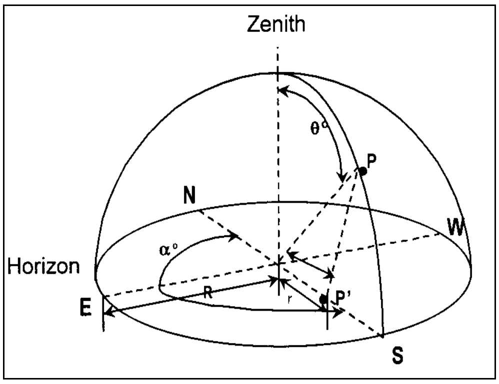

Fig. 1. *The polar hemispherical projection. Points within the sky hemisphere (P) will be projected (P') onto a circular image according to the geometry of the projection transformation (After Rich, 1990).*

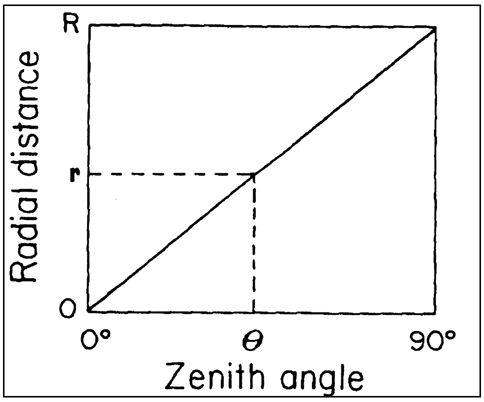

Fig. 2*. Polar projection: the zenith angle (è) of an object in the hemisphere is directly proportional with its radial distance (r) on the image plane.*