# A Comparison of Optical and Direct Methods for Monitoring the Seasonal Dynamics of Leaf Area Index in Deciduous Forests

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During the 1996 growing season the seasonal dynamics of the Leaf Area Index (LAI) were determined by 3 different methods in two forest types: a mixed oak (*Quercus robur* L.) – beech (*Fagus sylvatica* L.) stand and an ash dominated (*Fraxinus excelsior* L.) stand. The results obtained from the two indirect methods, i.e. hemispherical photography and LAI-2000 Plant Canopy Analyser (Li-COR), were compared with the results of the direct measurement of litter fall collected in litter trap systems.

In this study the direct method is considered to be the reference, giving the most accurate LAI-values. Both the hemispherical photography and the LAI-2000 PCA introduced an underestimation of LAI when the actual canopy leaf distribution in the crown layer deviates from a random distribution of leaf area in space as is found in the mixed oak/beech stand. However, when the condition of random leaf distribution is nearly fulfilled (ash stand), the LAI-2000 PCA gave LAI-values which were close to the results obtained from the direct method. Regression curves with $R^2>0.93$ could be calculated for both indirect methods.

**Keywords** leaf area index, mixed deciduous forest, LAI-2000 plant canopy analyser, hemispherical photography, litter trap
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# 1 Introduction

The description of the forest canopy structure is very important for studying the interaction between a forest and its environment. Knowledge of the canopy structure is useful to study processes such as the interception of light and precipitation, the turbulent transport of $CO_2$, the sensible and latent heat fluxes and the productivity of the forest. Also, when examining atmospheric deposition to the forest (Lovett et al. 1996), when modelling the water, carbon or nutrient cycle of the forest, or when studying stand structure and biodiversity (Ackerly and Bazzaz 1995, Poulson and Platt 1989), knowledge about the canopy structure is needed (McIntyre et al. 1991, Wang et al. 1992).

An important parameter giving information about the canopy structure is the Leaf Area Index (LAI). As most of the above mentioned processes are examined on a unit leaf area basis, the LAI is necessary for scaling up the results to the level of the forest stand or ecosystem. Many recent studies are concentrating on the effects of 'Global Change' on forest ecosystems. In order to model the carbon cycle and the effects of a predicted rise of the atmospheric $CO_2$ concentration (Watson et al. 1990) on forest ecosystems, knowledge of the LAI is indispensable. Furthermore LAI is also important as an indicator of the vitality of trees and it can be used for studying forest dynamics.

Many methods have been used to measure LAI (McIntyre et al. 1991): harvesting methods (Brenner et al. 1995, Whitford et al. 1995), litter traps (Cutini et al. 1998, Neumann et al. 1989), allometric relationships between tree diameter and total leaf area (Smith et al. 1991, Smith et al. 1993), inversion of light penetration through the canopy (Chen 1996, Gazarini et al. 1991) and hemispherical photography (Walter and Himmler 1996, Wang and Miller 1987). The last two are indirect methods and they are becoming increasingly more important (Kucharik et al. 1998) as they are less labour intensive and are able to supply LAI-data during the entire vegetation period. Hence it is important to have a good idea about the accuracy of these indirect methods.

The LAI depends on the forest type, the forest age and the moment of the growing season at which measurements are carried out. Of course the LAI of each forest type is strongly dependent of the biotic and climatic conditions at which the trees grow. The sum of these factors, together with the different methods used, results in widely different LAI-values spread throughout the literature.

Within this context, the study reported here had three main goals: (i) the quantitative determination of the LAI for two temperate deciduous forest types and the monitoring of its dynamics during the whole season, especially during leaf fall, (ii) the comparison of three independent methods to determine LAI in casu the LAI-2000 Plant Canopy Analyser (Li-COR), hemispherical photography and litter traps and (iii) the calculation of regression equations in order to convert the values obtained with the indirect methods to the values obtained with the direct method.

# 2 Material and Methods

## 2.1 Site Description

The study was conducted in the Aelmoeseneie forest in Gontrode (50°58´N, 03°48´E), located at about 15 km in the south-east direction of Gent (Belgium). The Aelmoeseneie forest belongs to the University of Gent and is managed by the Laboratory of Forestry. Two different forest stands were selected for this research because of the fact that each stand had known differences in total leaf area, and differences in the seasonal evolution and spatial distribution of this leaf area.

The first forest stand selected is dominated by oak (*Quercus robur* L.) and beech (*Fagus sylvatica* L.), which take up respectively 48.7% and 26.6% of the total basal area. The shrub layer consists mainly of hazel (*Corylus avellana* L.).

The tree species composition of the second forest stand selected is dominated by common ash (*Fraxinus excelsior* L.; 59.5% of the total basal area), mixed with maple (*Acer pseudoplatanus* L.; 15.8% of total basal area) and oak (*Quercus robur* L.; 10.6% of total basal area) and mainly rowan (*Sorbus aucuparia* L.) in the shrub layer.

The tree age in both stands is about 75 years and both stands are subjected to a regular management. In the oak/beech stand a thinning has been carried out during the winter of 1995, which produced the presence of gaps in the forest canopy. The ash stand has not been thinned and has therefore a more closed canopy. However, the ash stand is characterised by a SE to NW gradient in canopy density. Further information about the forest and on the experimental set-up can be found in Samson et al. (1996).

### 2.2 Light Models

Light models are used for determining the LAI by means of the light inversion technique. Numerous light models have appeared since the first one was reported by Monsi and Saeki (1953). An infinite number of statistical radiation models are possible, because every time leaves are characterised by a different statistical distribution, a new model is developed. Different statistical radiation models are elaborately described in Lemeur and Blad (1974). Models can be built for regular leaf dispersion, for clumped leaf dispersion, for random leaf dispersion, for variable leaf dispersion and even for different other dispersions. The Poisson model for random leaf dispersion, is the best known and the most applied one. It is also this model that has been applied in this research. The main condition for applying the Poisson model is a random leaf distribution.

### 2.3 Data Collection

#### *2.3.1 LAI-2000 Plant Canopy Analyser (Li-COR)*

Determination of the LAI with the LAI-2000 PCA is based on measurements of light transmittance for five zenith angles assuming an exponential model of light extinction (further information can be found in the manual – Li-COR Inc. 1992). However, due to the influence of stems and branches on the image detected by the sensor the LAI-2000 PCA measurement is rather a Plant Area Index (PAI) than a Leaf Area Index (LAI). The exponential model of light extinction is based on the assumptions that (i) the leaves are black i.e. they do not absorb nor reflect radiation, (ii) the leaves in the canopy are randomly distributed, (iii) the leaves are relatively small compared to the area of view of each ring and (iv) the azimuths of the leaves are randomly distributed (Li-COR Inc. 1992). When using the LAI-2000 PCA, certain measuring conditions must be fulfilled. The most important of these is the sky condition for which uniform overcast conditions are preferred. Making measurements at bright sunlight should be avoided, as this gives an underestimation of the LAI. The sunlight incident onto the leaves is being scattered in all directions, consequently the sensor doesn't 'see' the sunlit leaves and the LAI is underestimated.

Fig. 1 locates the experimental design for the three different methods applied. Measurements with the LAI-2000 PCA have been carried out at 11 sampling points (not indicated in Fig. 1) along 3 transects (indicated in Fig. 1 as T1, T2 and T3) in the oak/beech stand. In the ash stand, one 100 m transect with 20 sampling points has been selected for the experiments in order to cover the canopy density gradient. The number of sampling points has been determined according to the method described in the LAI-2000 PCA manual. This involves that LAI determination based on 6 readings has been carried out. This has been used to determine the number of replicates needed for a 95% confidence that the true LAI mean is within 10% of the measured LAI (Li-COR Inc. 1992).

A 45° view cap was used and the LAI-2000 PCA sensor was always directed towards the East. The optical sensor was levelled horizontally and held at breast height. As only one instrument was available, the free field measurements were conducted in a nearby clearing and immediately followed by the measurements in the forest. Attention was paid to the sky conditions, measurements were only carried out under uniform overcast sky.

LAI was determined during the leaf fall period of 1996, at 6 sampling dates in the oak/beech stand and at 5 dates in the ash stand. These values were compared with LAI values obtained with the other methods (hemispherical photography and leaf collection) at the same sampling dates.

In order to compare results from the LAI-2000 PCA with the other methods used, the experimental designs of the three methods were geared to each other (Fig. 1).

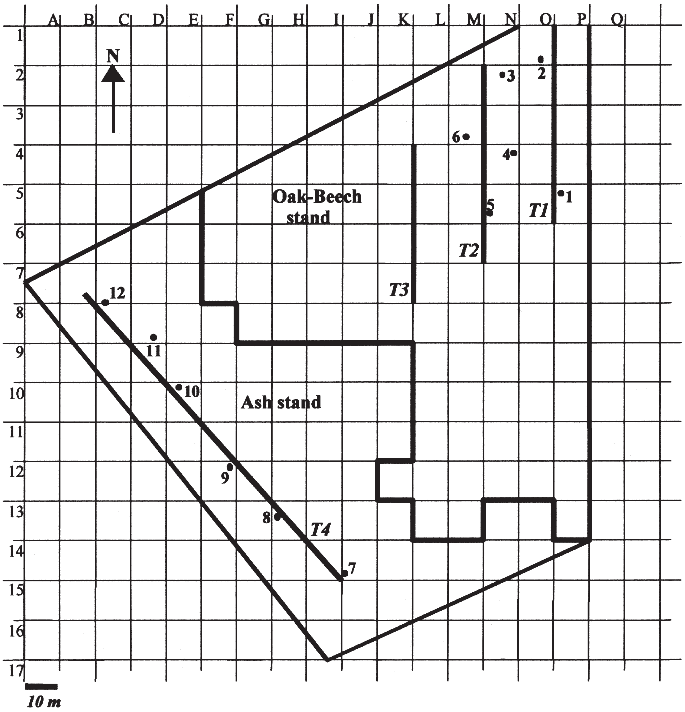


**Fig. 1.** Schematic representation of the oak/beech and ash forest stands, indicating the sampling methods used for the LAI-2000 PCA (T1–T4), the hemispherical photography and the collection of leaf litter (1–12).

### *2.3.2 Hemispherical Photography*

The photographs were taken at uniform overcast sky conditions with a fisheye lens (Fisheye Nikkor, f = 8 mm, 1:2.8) mounted on a manually operated Nikkon camera (Nikkormat). A black and white documentfilm (Agfaortho 25 ASA) was used in order to obtain a good picture contrast between the trees and the sky. Determination of shutter speed and diaphragm of the camera was carried out using a light sensor (Polaris Flash Meter). This sensor was placed at the top of the hemispherical lens in order to quantify the incoming radiation. At each sampling spot in the forest, 3 pictures were taken at 1m above the soil surface: one with shutter speed and diaphragm as indicated by the light sensor, one that was overexposed and one underexposed. The underexposed picture always showed the most detail and best contrast and, as such, has been used for further processing.

The photographs were computer processed using the HEMIPHOT software (Ter Steege 1994), a computer programme designed to analyse hemispherical photographs. This programme can determine the LAI in several ways, each of them based on inversion of the gap frequency and the exponential model for light extinction (see also Section 2.2). Determination of the LAI with HEMIPHOT was carried out using the Li-COR method, which means that LAI was calculated in the same way as done with the LAI-2000 Plant Canopy Analyser.

Determination of the LAI using hemispherical photography has been performed during the whole growing season of 1996, starting in May and ending in December. As the hemispherical lens has a larger integrating capacity than the LAI-2000 PCA (360° view instead of 45°), 6 photographs were taken in both forest stands at each sampling date. Fig. 1 shows the locations where the photographs were taken: in the oak/beech stand these spots were chosen at random and in the ash stand these spots were chosen along the 100 m transect used for the LAI-2000 PCA. This experimental set-up was chosen according to the distribution in canopy density in the stands as described above.

The hemispherical lens always records leaves, stems and branches analogously to the LAI-2000 PCA. Hence, the LAI value determined with both instruments is rather a PAI than a LAI. However, the expression LAI will be used throughout this paper.

### *2.3.3 Collection of Litter Fall*

Litter fall was collected from 15 August to 29 December 1996. In both forest stands, thirty self-constructed square litter traps (1 m×1 m) were used to collect the litter fall at a height of 1 m above the ground level. The size and height of the litter traps were based on the findings of McShane et al. (1983) and Morrison (1991). The experimental set-up of the litter traps was concentrated around the spots where hemispherical photographs were taken (Fig. 1). At each photographic spot 5 litter traps were installed: one in the centre, the others being displaced 5 m away from the central spot in the four main wind directions.

From August till December litter fall was collected every 2 weeks, leaf area and dry leaf biomass were determined for each tree species separately, as well as branch and fruit biomass. Determination of the leaf area was carried out with a Portable Area Meter (Li-COR, Li-3000), coupled at a Transparent Belt Conveyer (Li-COR, Li-3050 A). Afterwards the leaves were dried in an oven at 90 °C for 48 h and weighed to determine the dry weight.

# 3 Results

## 3.1 Indirect Methods

Table 1 shows the results obtained with both indirect methods in both forest stands. In the oak/beech stand the LAI obtained with the LAI-2000 PCA amounted to 3.98 on 18th September. It was at the end of October that leaf fall began. The minimum LAI value observed with the LAI-2000

**Table 1.** LAI values obtained for the oak/beech stand and the ash stand using the LAI-2000 PCA, hemispherical photography and leaf litter collection (DoY = Day of the Year). Only with hemispherical photography LAI values are obtained during the whole growing season of the year 1996.

| Date(DoY) | Oak/beech stand | | | Ash stand | | |
|---|---|---|---|---|---|---|
| | LAI-2000 PCA | LAI Photogr. | LAI leaf fall | LAI-2000 PCA | LAI Photogr. | LAI leaf fall |
| 13/5 (134) | | 2.42 (0.25/0.62) | | | 2.21 (0.11/0.28) | |
| 12/6 (164) | | 3.21 (0.31/0.75) | | | 3.31 (0.22/0.55) | |
| 3/7 (185) | | 3.35 (0.25/0.62) | | | 3.55 (0.39/0.95) | |
| 24/7 (206) | | 3.47 (0.18/0.44) | | | 4.05 (0.30/0.72) | |
| 15/8 (228) | | 3.34 (0.20/0.50) | 5.52 (0.10/0.55) | | 3.53 (0.20/0.50) | 4.53 (0.11/0.60) |
| 27/8 (240) | | 3.00 (0.12/0.30) | | | 3.29 (0.15/0.36) | |
| 18/9 (262) | 3.98 (0.17/0.56) | 3.68 (0.23/0.56) | 5.08 (0.10/0.55) | | 3.64 (0.26/0.63) | 4.26 (0.11/0.60) |
| 30/9 (274) | | 3.38 (0.20/0.48) | | 4.56 (0.18/0.81) | 3.43 (0.24/0.58) | |
| 10/10(284) | 3.37 (0.17/0.56) | 3.13 (0.21/0.52) | 4.60 (0.09/0.49) | 4.22 (0.17/0.76) | 3.21 (0.22/0.54) | 4.02 (0.11/0.60) |
| 25/10(299) | 3.58 (0.16/0.53) | | | 3.73 (0.18/0.81) | | |
| 29/10(303) | 2.94 (0.12/0.40) | 2.91 (0.45/1.10) | 2.95 (0.07/0.38) | 3.15 (0.15/0.67) | 3.14 (0.31/0.76) | 2.59 (0.07/0.38) |
| 12/11(317) | | 1.55 (0.04/0.09) | 1.54 (0.04/0.22) | | 2.14 (0.07/0.16) | 1.64 (0.06/0.33) |
| 19/11(324) | | 1.42 (0.10/0.42) | | | 1.80 (0.04/0.10) | |
| 3/12 (338) | 0.99 (0.06/0.20) | 1.11 (0.16/0.38) | 0.35 (0.02/0.11) | 1.17 (0.04/0.18) | 1.39 (0.17/0.41) | 0.31 (0.03/0.16) |
| 29/12(364) | 0.90 (0.07/0.23) | 1.24 (0.03/0.06) | 0.00 | | 1.19 (0.08/0.19) | 0.00 |

Note: In parentheses the standard error on the mean (SE) and the standard error on 1 measurement (SEL).

PCA was 0.9 on 29th December. In the ash stand a similar succession of the LAI was observed: leaf fall began at the end of October, and at the beginning of December the LAI amounted to 1.17. As results of the hemispherical photography are obtained for the whole growing season, they show a remarkable and similar succession in both forest stands (Table 1). On 13th May, just after bud burst, the LAI amounted 2.42 in the oak/beech stand and 2.21 in the ash stand. The LAI gradually increased and reached in both forest stands a first maximum on 24th July (3.47 in oak/beech stand, 4.05 in ash stand). From that moment on the LAI decreased gradually to a minimum value at the end of August, and then it increased again to a second maximum value on 18th September. Real autumn leaf fall started at the end of October. At the end of December the LAI amounted 1.24 in the oak/beech stand (due to weather conditions the measured LAI value of the 3rd December is lower than the LAI on 29th December) and 1.19 in the ash stand. The LAI values obtained at the end of December with both methods cannot be considered as a real Leaf Area Index (at that time no leaves were left in the tree canopy), but it indicates the maximum value of the Wood Area Index (WAI). The WAI is a measure for the amount of branches and stems 'seen' either through the hemispherical lens or the sensor of the LAI-2000 PCA.

The standard errors on an individual measurement (SEL) shown in Table 1 are rather high for both indirect methods and at any measuring date, and they indicate the heterogeneity of the canopy density in the ash stand and the gap frequency in the oak/beech stand. The standard errors (SEL) on the LAI values obtained with the LAI-2000 PCA in the ash stand are remarkably high, which is due to the gradient in canopy closure along the 100 m transect, as was also noticeable in the field. Generally, the standard error on the mean (SE)(Table 1) obtained with hemispherical photography is higher than the SE from the LAI-2000 PCA, which is probably due to the lower number (6) of replicates for this former method. The exceptionally large standard error observed with hemispherical photography in both stands on 29th October could be caused by the irregularity of the leaf fall depending on the tree species.

Taking in consideration the large confidence intervals for the LAI values, the number of replicates needed to know the maximal LAI with 95% confidence within a 10% deviation of the mean has been calculated. In the oak/beech stand the number of replicates needed with the LAI-2000 PCA amounted 11 and in the ash stand 15. For hemispherical photography the number of replicates needed was 12 for the oak/beech stand and 14 for the ash stand.

### 3.2 Collection of Litter Fall

In the oak/beech stand (Table 1) the maximal LAI value was 5.52 in the middle of August. At the beginning of October the LAI had only decreased with one unit, while at the end of October already 50 % of the leaf area had fallen. Leaf fall began at about the 10th October and finished at the end of December (29th). In the ash stand (Table 1) the maximal LAI amounted 4.53 (middle of August). Again shedding of the leaves began at about the 10th October and ended at the end of December (29th).

The number of replicates needed to know the maximal LAI with this method with the same precision as stated above amounts 7 for the oak/beech stand and 10 for the ash stand.

In the oak/beech stand (Fig. 2), beech contributed to the largest part of the LAI (54%), followed by oak (39%), whereas the share in the total basal area is only 26.6% for beech and 48.7% for oak. This means that the total leaf area of a beech is larger than the leaf area of an oak with the same diameter. This can be attributed to the high shade tolerance of beech compared to oak. Leaves of beech were also found to fall earlier than leaves of oak.

The tree species composition of the LAI in the ash stand is more complex than the composition in the oak/beech stand (Fig. 2). Ash has the largest part of the total LAI (38%), followed by maple (26%) and Hazel (15%) in the shrub layer. As the share of ash in the total basal area of the stand is 59.5%, it becomes clear that ash has a very low leaf area, which is typical for the light demanding character of this tree species. The leaves of ash fall earlier than those of the other tree species, which is in this case probably intensified by the dominant position of the ash in the upper storey,

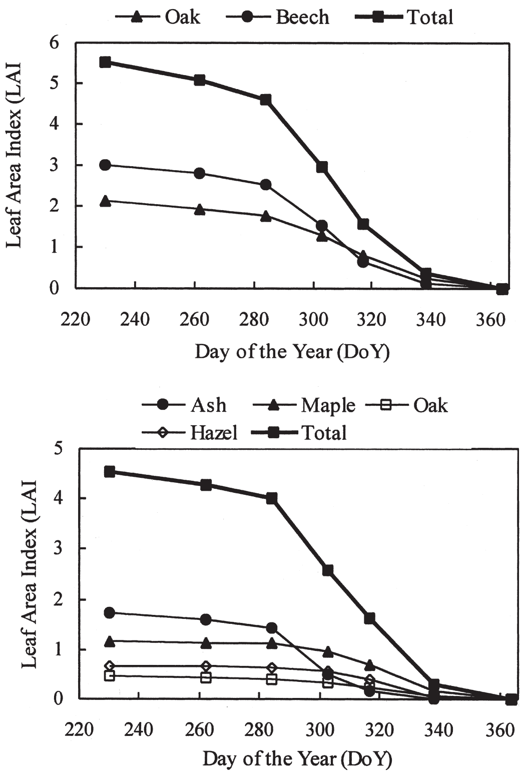


**Fig. 2.** Evolution of the LAI during the leaf fall period of 1996 in the oak/beech stand (above) and the ash stand (below). Data were obtained from the collection of leaf litter fall. Total stand LAI is represented as well as the separate contributions of the most important tree species in each stand.

exposed to a more severe microclimate (higher wind speed, higher diurnal temperature differences, higher striking force of rain, …). Trees in a less dominant position or in the shrub layer were found to lose their leaves later.

### 3.3 Comparison between Methods

#### *3.3.1 Oak/Beech Stand*

Means were compared to each other using their 95% confidence intervals (Fig. 3). Those values for which the 95% confidence intervals do not overlap are defined as significantly different.

For the oak/beech stand, the results obtained with the LAI-2000 PCA and hemispherical photography are not significantly different except for the 29th December (day 364 – see Fig. 3). At that moment the LAI-2000 PCA gives a significant underestimation of the WAI in comparison with the hemispherical photographs. Although the differences are not significant at any other moment, Fig. 3 suggests that the hemispherical photographs yield lower LAI-values than the LAI-2000 PCA for the higher LAI values and vice versa for the lower LAI values. Similar results were found by Wang et al. (1992), working in a mixed oak forest.

For all except two dates the LAI values obtained with the LAI-2000 PCA are significantly different from the LAI obtained measuring litter fall. The higher LAI values are underestimated with the LAI-2000 PCA, while the lower LAI values are overestimated.

In comparison with the LAI values obtained from the collection of litter fall, the hemispherical photographs give a significant, even larger underestimation of the LAI, compared to the underestimation observed with the LAI-2000 PCA, for the high LAI values. Also the overestimation of the lower LAI values with the hemispherical photographs is larger than the overestimation with the LAI-2000 PCA.

#### *3.3.2 Ash Stand*

In contrast with the measurements in the oak/beech stand, the results of the LAI-2000 PCA and the results obtained with hemispherical photography do clearly differ. For higher LAI values the photographs significantly underestimate the LAI-2000 PCA results (Fig. 3 – days 274 and 284). For the lower LAI values, the hemispherical photographs tend to give a small overestimation of the LAI obtained with the LAI-2000 PCA, but this is not significant.

When comparing the LAI-2000 PCA results with the results from the collection of leaf litter, Fig. 3 shows that for the higher LAI values, the LAI-2000 PCA gives no significantly different values. For the lower LAI values, the LAI-2000 PCA overestimates the LAI significantly, due to the absence of a correction of the

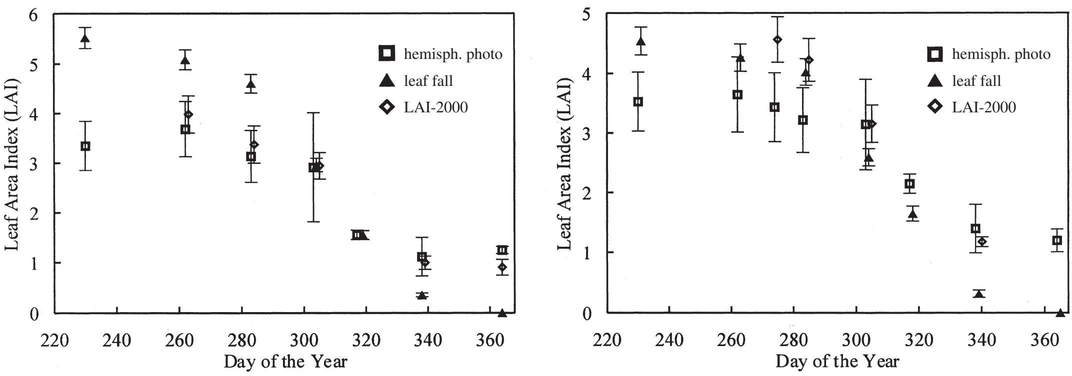


**Fig. 3.** LAI of the oak/beech stand (left) and the ash stand (right) during the leaf fall period, determined with the three different methods. The flags indicate the 95% confidence interval. Those measurements for which the 95% confidence intervals do not overlap, are defined as significantly different.

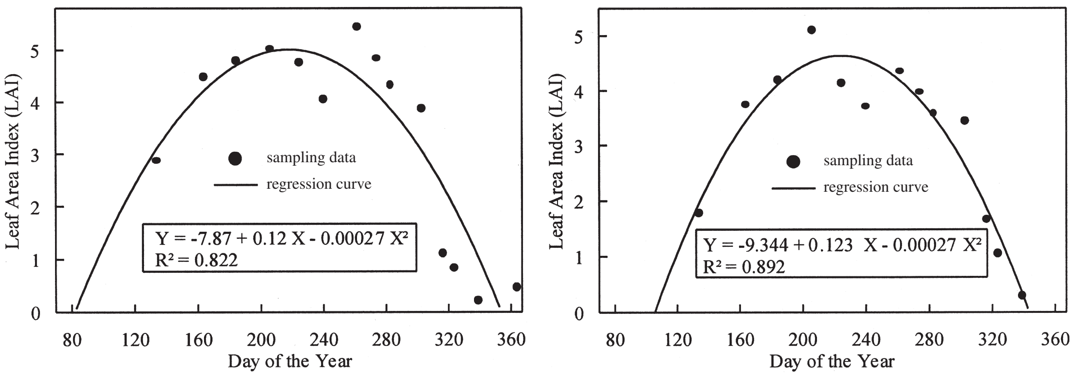


**Fig. 4.** Model of the evolution of the LAI of the oak/beech stand (left) and the ash stand (right) during the growing season. LAI values obtained with the hemispherical photographs were corrected using the calculated regressions (see Table 2). The best fitting curve (equation shown in the figures together with the determination coefficient) was calculated for these corrected LAI values.

LAI values accounting for the influence of stems and branches on the image.

For the higher LAI values, the hemispherical photographs give a significant underestimation of the LAI obtained from the collection of leaf litter (Fig. 3). For the lower LAI values, the hemispherical photographs significantly overestimate the LAI obtained from the collection of leaf litter, for the same reason as mentioned above for the LAI-2000 PCA.

### 3.4 Regression Equations

As the direct method is assumed to be the most correct for estimating LAI, this method serves as reference for the performance of the indirect methods. In order to be able to use the indirect methods to determine the LAI in the future, regression equations have been calculated between the results of the indirect and the direct methods for both forest stands (Table 2). Linear regression curves gave the highest determination coefficient: all $R^2$ are higher than 0.93.

**Table 2.** Regression equations calculated between the LAI of both forest stands obtained with the indirect and the direct methods (X = LAI from LAI-2000 PCA; X' = LAI from photography; Y = LAI from leaf litter; $R^2$ = determination coefficient).

| Forest type | Regression equation | |
|---|---|---|
| Oak/beech | $Y = -1.42 + 1.65 \cdot X$ | ($R^2 = 0.98$) |
| | $Y = -2.07 + 2.04 \cdot X'$ | ($R^2 = 0.93$) |
| Ash | $Y = -1.09 + 1.19 \cdot X$ | ($R^2 = 0.998$) |
| | $Y = -2.21 + 1.80 \cdot X'$ | ($R^2 = 0.95$) |

These regression curves (Table 2) have been used to correct the photographic LAI values for both forest types. These corrected data were then used to calculate the best fitting curve (model) which simulates the evolution of the LAI of both forest stands during the growing season. Results for the oak/beech stand and the ash stand are shown in Fig. 4. The calculated equations have a good fit ($R^2 = 0.82$ and 0.89), but they do not show the detailed seasonal course of the LAI.

# 4 Discussion

## 4.1 Direct and Indirect Methods

The number of replicates needed for a 95% confidence that the mean LAI is within 10% of the measured LAI indicates that the sampling strategy with the LAI-2000 PCA was adequate to reach this precision. On the contrary these results show that not enough hemispherical photographs were taken in each stand to reach the above stated precision. It is also clear that both indirect methods, the LAI-2000 PCA and hemispherical photography, have about the same spatial integration and require the same amount of replicates. For the collection of leaf litter the sampling strategy was satisfactory, as this method requires much less than 30 replicates to obtain maximal LAI values with the above stated precision.

PAI values obtained with the LAI-2000 PCA and with hemispherical photography have not been corrected to obtain LAI. It was not possible to use the WAI measured at the end of December to correct PAI values. Kucharick et al. (1998) showed in their study of boreal forest architecture for both coniferous and deciduous species that branches are preferentially shaded by other non-woody elements (e.g. shoots or leaves), and are not positioned randomly with respect to leaves or shoots in the canopy. This brings about that the detectable WAI value changes during the growing season and cannot be linearly subtracted from the LAI. In summer, when trees have their full leaf cover, the detectable WAI will be lower than the value obtained in December, when no leaves are left in the tree canopy (Dufrêne and Bréda 1995).

As the same processing method for determining the LAI has been used for the hemispherical photographs and for the LAI-2000 PCA, both methods have some similar technical problems. The weather conditions have a large influence on the LAI determined with both methods. Technically, measurements should only be made under a uniform overcast sky. When measurements are made under conditions of fast moving clouds or a sunny sky, this will underestimate the LAI. Furthermore, the influence of the sky conditions is different depending on the canopy structure. With a clumped, non-homogeneous canopy structure the underestimation of the LAI will even be larger, due to the very local penetration of rays of radiation through the canopy. For these reasons measurements with both methods have only been performed under uniform overcast sky conditions. Experience has learned that especially the LAI-2000 PCA is highly sensitive to these sky conditions, which confirms the findings of other authors (Chason et al. 1991, Welles and Norman 1991) that the LAI-2000 PCA only performs well under ideal sky conditions.

Better results with both indirect methods might be obtained by omitting detector ring 5 and possibly also detector ring 4 (Chason et al. 1991, Cutini et al. 1998, Dufrêne and Bréda 1995, Strachan and McCaughey 1996).

Concerning the use of the hemispherical photographs, some additional technical problems, which are inherent to this method, have been experienced. These problems are the adjustment of the diaphragm and the shutter speed. Depending on the exposure of the photofilm, the quality of the pictures varies strongly. Chen et al.

(1991) investigated this influence of shutter speed and diaphragm on the results obtained with the hemispherical photographs. They conclude that hemispherical photography can be a more accurate method to determine LAI in comparison with the LAI-2000 PCA, when the photographs are underexposed by approximately 4.5 stops. Their results indicate that good estimates of the LAI can be obtained using fisheye photography when film exposure is carefully selected. Although underexposure of the film indeed yielded the best results, the underexposure used in this research was possibly not large enough to obtain a correct value of the effective LAI. Furthermore the results from the photographs are subject to errors in the film developing and printing as well, which is also remarked by Chen et al. (1991). Therefore it is important to have a standard film processing procedure as has been used in this research, in order to avoid irregularities in LAI values resulting from processing errors.

### 4.2 Comparison between Indirect and Direct Methods

By measuring simultaneously with the different methods, it was possible to calculate useful regression curves between the LAI obtained with the indirect and the direct methods (Table 2). These regressions make it possible to calculate corrected LAI values from values resulting from the LAI-2000 PCA or hemispherical photography. However, this is possible as long as no changes in the canopy structure are made (wind throw, felling of trees, …).

In the oak/beech stand, the LAI-2000 PCA significantly underestimated high LAI values (found by the leaf litter method). Low LAI values were overestimated. Also in the ash stand this overestimation was observed but there was no significant difference found for the high LAI values. These results are consistent with the findings of Chason et al. (1991) and Fassnacht et al. (1994). As mentioned before, the overestimation can be attributed to the fact that LAI 2000 values have not been corrected for the influence of stems and branches detected by the sensor (WAI). However, when this linear correction would have been applied, the underestimation of the higher LAI values would have been even larger.

In the ash stand, a good accordance of the LAI-2000 PCA and the direct measurements is found. This confirms the fact that the exponential model, used to characterise the light extinction, is most appropriate for homogeneous canopy layers with a small amount of clumping, as is the case for the ash stand.

This also explains the underestimation of the high LAI values in the oak/beech stand: recent thinning created a very clumped canopy layer. Also Cutini et al. (1998) found this underestimation comparing thinned and unthinned stands. A negative binomial light extinction model, as described by Lemeur and Blad (1974), might be a better choice to calculate the LAI in the oak/beech stand.

For the hemispherical photographs, a significant underestimation of high and an overestimation of low LAI values was observed in the oak/beech stand as well as in the ash stand. In the latter however the underestimation of the LAI by the photographs is smaller than in the oak/beech stand. This means that in both forest types a certain amount of clumping is present in the canopy, though much more in the oak/beech stand.

In contradiction with the results of this research, Strachan and Mc Caughey (1996) and Wang et al. (1992) found respectively in a heterogeneous deciduous forest and in an oak forest, that for the higher LAI values the hemispherical photographs gave a small overestimation of the LAI-2000 PCA values. The use of a 45° view cap mounted on the sensor of the LAI-2000 PCA is probably responsible for the absence of underestimation of the LAI using the LAI-2000 PCA in the ash stand. The LAI determined with an indirect method is proportional to the logarithm of the gap fraction, so the proper way to average gap fractions is to average their logarithms. This in fact is how the LAI-2000 PCA averages multiple B (below canopy) readings in a file. However, each individual B reading is a linear average of the radiation from whatever azimuthal view range the sensor can see, as determined by the view cap. Problems can arise if the sensor sees dense foliage in one direction and little or no foliage in another direction at the time a B reading is recorded, because the gap in the canopy will be 'over weighted', and LAI will be underestimated. A way to avoid this problem is to use a view cap to restrict the sensor's field of view, so that dense and sparse regions of the canopy are included in separate B readings. It can be concluded that the larger the field of view is, the larger the underestimation will be. Therefore it could be interesting to use a kind of view cap for the processing of the photographs with HEMIPHOT too.

Concerning the use of the hemispherical photographs, it is clear that in both forest types the exponential model for light extinction was not appropriate and that another light extinction model (e.g. the negative binomial model) should be used. The underestimation of the LAI by the hemispherical photographs can also partially be due to the exposure and development of the film. The use of a digital camera would overcome some of these technical problems, mainly those concerning the development of the photofilm.

From the practical point of view, each method has its advantages and disadvantages. Collecting leaf litter to determine the LAI is the most precise, but also the most labour intensive method. Hemispherical photography is less labour intensive, but gives no correct LAI values in comparison with litter collection, due to the clumping of the canopy. Furthermore hemispherical photography has other uncertainties like exposure and development of the film and the weather conditions needed to make measurements. Due to the low performance of the photographs, it is necessary to do a detailed preliminary investigation on the canopy structure, before using this method.

The LAI-2000 PCA finally gives rather good results if the canopy is not strongly clumped and if a view cap is used, but requires very strict uniform overcast sky conditions to carry out the measurements. However, the LAI-2000 PCA is the least time consuming method to determine LAI, once a regression curve as in Table 2 has been calculated.

# References

Ackerly, D.D. & Bazzaz, F.A. 1995. Seedling crown orientation and interception of diffuse radiaton in tropical forest gaps. Ecology 76: 1134–1146.

Brenner, A.J., Cueto-Romero, M., Garcia-Haro, J., Gilabert, M.A., Incoll, L.D., Martinez-Fernandez, J., Porter, E., Pugnaire, F.I. & Younis, M.T. 1995. A comparison of direct and indirect methods for measuring leaf and surface areas of individual bushes. Plant Cell and Environment 18: 1332–1340.

Chason, J.W., Baldocchi, D.D. & Huston, M.A. 1991. A comparison of direct and indirect methods for estimating forest canopy leaf area. Agricultural and Forest Meteorology 57: 107–128.

Chen, J.M. 1996. Optically-based methods for measuring seasonal variation of leaf area index in boreal conifer stands. Agricultural and Forest Meteorology 80: 135–163.

— , Black, T.A. & Adams, R.S. 1991. Evaluation of hemispherical photography for determining plant area index and geometry of a forest stand. Agricultural and Forest Meteorology 56: 129–143.

Cutini, A., Matteucci, G. & Mugnozza, G.S. 1998. Estimation of leaf area index with the Li-Cor LAI 2000 in deciduous forests. Forest Ecology and Management 105: 55–65.

Dufrêne, E. & Bréda, N. 1995. Estimation of deciduous forest leaf area index using direct and indirect methods. Oecologia 104: 156–162.

Fassnacht, K.S., Gower, S.T., Norman, J.M. & McMurtrie, R.E. 1994. A comparison of optical and direct methods for estimating foliage surface area index in forests. Agricultural and Forest Meteorology 71: 183–207.

Gazarini, L.C., Araujo, M.C.C., Borralho, N. & Pereira, J.S. 1991. Plant area index in Eucalyptus globulus plantations determined indirectly by a light interception method. Tree Physiology 7: 107–113.

Kucharik, C.J., Norman J.M. & Gower, S.T. 1998. Measurements of branch area and adjusting leaf area index indirect measurements. Agricultural and Forest Meteorology 91: 69–88.

Lemeur, R. & Blad, B.L. 1974. A critical review of light models for estimating the shortwave radiation regime of plant canopies. Agricultural Meteorology 14: 255–286.

Li-COR Inc. 1992. LAI-2000: Plant Canopy Analyzer. Instruction manual. Lincoln, Nebraska. 174 p.

Lovett, G.M., Nolan, S.S., Driscoll, C.T. & Fahey, T. 1996. Factors regulating throughfall flux in a New Hampshire forested landscape. Canadian Journal of Forest Research 26: 2134–2144.

McIntyre, B.M., Scholl, M.A. & Sigmon, J.T. 1991. A quantitative description of a deciduous forest canopy using a photographic technique. Forest Science 36: 381–393.

McShane, M.C., Carlile, D.W. & Hinds, W.T. 1983. The effect of collector size on forest litter fall collection and analysis. Canadian Journal of Forest Research 13: 1037–1042.

Monsi, M. & Saeki, T. 1953. Uber den Lichtfaktor in den Pflanzengesellschaften und seine Bedeutung fur die Stoffproduktion. Japanese Journal for Botany 14: 22–52.

Morrison, I.K. 1991. Effect of trap dimensions on litter fall collected in an Acer saccharum stand in northern Ontario. Canadian Journal of Forest Research 21: 939–941.

Neumann, H.H., Den Hartog, G. & Shaw, R.H. 1989. Leaf area measurement based on hemispheric photographs and leaf litter collection in a deciduous forest during autumn leaf fall. Agricultural and Forest Meteorology 45: 325–345.

Poulson, T.L. & Platt, W.J. 1989. Gap light regimes influence canopy tree diversity. Ecology 70: 553–555.

Samson, R., Nachtergale, L., Schauvliege, M., Lemeur, R. & Lust, N. 1996. Experimental set-up for biogeochemical research in the mixed deciduous forest Aelmoeseneie (East-Flanders). Silva Gandavensis 61: 1–14.

Smith, F.W., Sampson, D.A. & Long, J.N. 1991. Comparison of leaf area index estimates from tree allometrics and measured light interception. Forest Science 37: 1682–1688.

Smith, N.J., Chen, J.M. & Black, T.A. 1993. Effects of clumping on estimates of stand leaf area index using the Li-COR LAI-2000. Canadian Journal Forest Research 23: 1940–1943.

Strachan, I.B. & McCaughey, J.H. 1996. Spatial and vertical leaf area index of a deciduous forest resolved using the LAI-2000 Plant Canopy Analyzer. Forest Science 42: 176–181.

Ter Steege, H. 1994. HEMIPHOT: A programme to analyze vegetation indices, light and light quality from hemispherical photographs. Wageningen, Tropenbos documents 3: Stichting Tropenbos. 44 p.

Walter, J.M.N. & Himmler, C.G. 1996. Spatial heterogeneity of a Scots pine canopy: an assessment by hemispherical photographs. Canadian Journal of Forest Research 26: 1610–1619.

Wang, Y.S. & Miller, D.R. 1987. Callibration of the hemispherical photographic technique to measure leaf area index distributions in hardwood forests. Forest Science 33: 210–216.

— , Miller, D.R., Welles, J.M. & Heisler, G.M. 1992. Spatial variability of canopy foliage in an oak forest estimated with fisheye sensors. Forest Science 38: 854–865.

Watson, R.T., Rodhe, H., Oeshger, H. & Siegenthaler, U. 1990. Greenhouse gases and aerosols. In: Houghton, J.T., Jenkins, G.J. & Ephraums, J.J. (eds.). Climate change. The IPCC scientific assessment. World Meteorological Organization, United Nations Environment Programme. Cambridge University Press, Cambridge. p. 1–40.

Welles, J.M. & Norman, J.M. 1991. Instrument for indirect measurement of canopy architecture. Agronomy Journal 83: 818–825.

Whitford, K.R., Colquhoun, I.J., Lang, A.R.G. & Harper, B.M. 1995. Measuring leaf area index in a sparse eucalypt forest: a comparison of estimates from direct measurement, hemispherical photography, sunlight transmittance and allometric regression. Agricultural and Forest Meteorology 74: 237–249.

*Total of 30 references*