

Leaf area index and canopy stratification in Scots pine (*Pinus sylvestris* L.) stands

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Abstract. In order to assess the contribution of each layer to effective leaf area index (LAI) in stratified forest canopies, two Scots pine stands were selected in Haguenau forest, Alsace, France. One stand, 80 years old, had a sparse tree layer and a dense herb layer. The other stand, 50 years old, had a closed tree layer and dense herb and shrub layers. Hemispherical photographs, taken at 10-metre intervals along transects beneath each layer, were digitized and analysed. In the two-layered stand, mean LAI was 0.9 for herbs and 1.5 for trees, contributing 37% and 63%, respectively, to total LAI. A positive and significant correlation was found between layers, suggesting that the herb layer had not yet adjusted to the recent thinning of the stand. In the three-layered stand, mean LAI was 1.1 for herbs, 0.4 for shrubs and 2.1 for trees, a contribution of 31%, 11% and 58%, respectively, to total LAI. The positive and significant correlation for LAI among layers may be explained by the presence of a mixture of light demanding and shade-tolerant species in the undergrowth. Horizontal spatial auto-covariance of estimates was not significant, denoting adequate sampling interval for statistically independent measurements. Such *in situ* assessments of LAI, differentiating vegetation strata, are useful from the perspective of remote sensing of forests, since undergrowth plays an important role in the integrated spectral response of whole canopies.

1. Introduction

Leaf area index (LAI) is used in numerous models of vegetation dynamics and functioning as a structural and functional descriptor (Botkin 1993, Ehleringer and

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Field 1993, Landsberg and Gower 1997). LAI is difficult to assess in tall forests through direct methods, like stratified clipping techniques (Hutchison *et al.* 1986), allometric relationships (Pereira *et al.* 1997) and litter collections (Dufrêne and Bréda 1995). These methods, considered as reference, are often site specific and have a limited spatial/temporal value. To overcome such difficulties, indirect optical methods have been made available. Most of them are based on gap fraction and gap size distribution theory. Instruments to acquire data use a variety of fish-eye and radiation sensors. Owing to their flexibility in the field, optical methods have become a standard, allowing for intensive spatial and temporal sampling through transects and grids over large areas. See for example Chen (1996), Welles and Cohen (1996), Kucharik *et al.* (1997), Gower *et al.* (1999) for recent reviews and perspectives.

Forests offer a specific challenge due to tree dimensions, architectural heterogeneity and spatial/temporal variability of foliage dispersion and dynamics. From a remote sensing perspective, an understory, a herb layer and/or a shrub layer, particularly in sparse forest canopies and woodlands, may contribute significantly to the integrated canopy radiance. These complexities add to the presence of non-photosynthetic surfaces—water bodies, litter, soil, rock, bark—together with plant and relief shadow, all of which influence the whole radiometric signal (Spanner *et al.* 1990, Price 1993, Hall *et al.* 1995, Raffy and Bréda 1998, Chen 1999, Chen *et al.* 1999).

Although a substantial effort has been devoted to assess foliage vertical profiles (Halldin 1985, Heiderich 1989, Hutchison *et al.* 1986, Vose *et al.* 1995), few investigations focus on horizontal variability of LAI (Joffre *et al.* 1996, Walter and Grégoire 1996). Even fewer studies explicitly link horizontal to vertical patterns of forest LAI and to plant coverage (Houssard and Escarré 1981, Wang *et al.* 1992, Strachan and McCaughey 1996). In order to analyse the effect of canopy stratification on horizontal and vertical leaf area index and canopy cover distributions, two mature Scots pine stands were chosen in Alsace, France. One stand is relatively open, horizontally heterogeneous, and has a dense herb layer. The other stand is more closed, heterogeneous both vertically and horizontally. It has a herb layer plus a woody understory. Thus, the objectives of the study were to: (1) determine the contributions of the understory and the upper canopy to total canopy LAI and canopy cover, and (2) analyse their spatial correlation. The investigation was based on hemispherical photography, a close-range remote sensing technique (Rich 1990).

2. Theory and definitions

LAI and canopy cover were estimated through gap fraction theory and analyses. Gap fraction is the fraction of open sky (range 0–1) to a view direction (zenith angle θ , azimuth angle φ), or the probability of non-interception $P_0(\theta, \varphi)$ of a ray of light passing through the canopy to that direction. Canopy openness (CO) measures the fraction of sky visible through the canopy, as related to the surface of the hemisphere (Mitchell and Whitmore 1993, ter Steege 1997, Frazer *et al.* 1997, Walter 1999–2001). It is calculated as a percentage as $CO\% = 100 \frac{\sum_1^N P_0(\theta, \varphi)}{n} \{(\cos \theta_1 - \cos \theta_2)/n\}$, where θ_1 is the smallest zenith angle and the largest zenith angle from successive hemispherical rings, n is the number of divisions of azimuth angles, and N is the number of angular regions used in the application. Canopy cover (CC) is the complement to CO. Therefore, it is not the vertical projection of aerial parts of vegetation, as the classical definition used in plant ecology. Instead, it is an angular cover over all, or selected, directions of the hemisphere. However, gap fractions measured near zenith (for example at 7.5° off zenith, a 15° field of view, FOV),

supply a CC which compares to the classical definition, provided an appropriate sampling effort be done to account for the high spatial variability of zenith gap fraction. CO and CC are useful for monitoring canopy/crown closure, foliage phenology and response to environmental impact and stress.

LAI can be defined in several ways (Barclay 1998). As used here, LAI is half the total surface area of foliage elements (total foliage, including leaves, needles, flowers, fruits, branches, trunks) per unit ground surface area, on a projected basis. In fact, it is a plant area index (PAI). For theoretical justification see Lang (1991), Chen and Black (1992), and Chen (1996). The classical theory to derive LAI estimates is based on the Poisson model of gap frequencies, assuming that foliage elements are randomly dispersed in independent horizontal layers, symmetrically distributed in azimuth and distributed with any inclination angle. Nilson (1971) proposed a Markov model, assuming dependent layers, to take into account clumped dispersion of foliage elements. Thus, the angular information contained in gap fractions can be written (e.g. Kucharik *et al.* 1999): $P(\theta) = \exp \{-G(\theta)/\Omega_e(\theta)LS\}$, where $P(\theta)$ is the probability of a radiation beam penetrating through the foliage at zenith angle θ , $G(\theta)$ is the fraction of foliage area projected onto a plane perpendicular to direction θ , L is the foliage area index which has to be estimated, $\Omega_e(\theta)$ is a foliage element clumping factor at the canopy level, and S is the path length of a ray of light to direction θ . $P(\theta)$ is measured on hemispherical photographs and S is given by $1/\cos\theta$. $G(\theta)$ can be estimated. It is equal to 0.5 if the angular distribution of the normal to foliage elements is a sphere, a realistic assumption in many closed-canopy forests. For random canopies $\Omega_e(\theta) = 1$. Departure from randomness ($\Omega_e(\theta) < 1$) is common, mainly in coniferous forests and sparse canopies. Thus, $\Omega_e(\theta)$ needs to be determined by an independent method, not to mention the needle-to-shoot-area-ratio (γ_e), which accounts for clumping at the shoot level, specific to conifers (Stenberg *et al.* 1994, Chen and Cihlar 1995). For this reason, Black *et al.* (1991) defined an 'effective' LAI, or L_e , which is the composite $L\Omega_e(\theta)$. Therefore, estimates from optical methods are effective plant area indices, which account neither for clumping nor for separating leaves from non-photosynthetic support material, nor for distinguishing species. For more details and recent developments in the field, see e.g. Chen and Cihlar (1995), Chen (1996), Chen and Leblanc (1997), Fournier *et al.* (1997), Chen *et al.* (1999) and Kucharik *et al.* (1999).

3. Methods

3.1. Study sites

Two Scots pine (*Pinus sylvestris* L.) stands were selected in a 14000 ha continuous forest tract on a lowland Pliocene–Quaternary terrace, with acid sandy or clayey sediments and horizontal topography, at Haguenau, 25 km north of Strasbourg, France (48°50'N, 7°55'E, altitude 140 m above sea level). The stands are part of a typical silviculture mosaic of parcels intensively managed, ranging from 17 to 32 ha in extent and varying in age, density and height (Walter and Grégoire 1996, Soudani 1999).

Stand 50 (Office National des Forêts, Division de Haguenau) has a two-layered vegetation. The herbaceous layer, about 0.5 m in height, is a mixture of *Pteridium aquilinum* (L.) Kuhn (bracken), *Vaccinium myrtillus* L. (blueberries), and *Molinia coerulea* (L.) Moench (purple moorgrass) dominating in more open sites. The tree layer, 30 m in height, contains 80-year old Scots pines. Sparse *Picea excelsa* LK (Norway spruce), *Quercus petraea* (Mattuschka) Liebl. (sessile oak), *Fagus sylvatica*

L. (beech), *Betula pubescens* Ehrh. (birch), *Ilex aquifolium* L. (holly), and *Frangula alnus* Miller (alder berry), were found. Stand 69 has a three-layered vegetation. The herbaceous layer has the same species as found in stand 50, but bracken is particularly vigorous, reaching 2 m. The dense 3–6 m understory is dominated by alder berry, accompanied by *Sorbus aucuparia* L. (mountain ash) and holly. The upper layer is a 50-year old Scots pine canopy, 25 m in height. Table 1 summarizes measurement data from both stands. More details can be found in Soudani (1999).

3.2. Photographic data acquisition and exploitation

In each stand, and for each vegetation layer, hemispherical photographs were taken at 10 m intervals along transects 350 m in length, at least 50 m distant from parcel limits to avoid edge effects. A 10 mm OP-Nikkor® 1:5.6 (180° viewing angle, orthographic projection) was mounted on a Nikon® camera loaded with fine grain and high contrast black and white negatives (TMAX™ 100 Kodak™), fixed on a tripod, levelled and oriented to magnetic North. In order to take into account differing vegetation layers, levels above ground were fixed at 0.15 m (above ground, beneath the herbaceous layers in both stands), 1.7 m (above herb layer, beneath shrub layer in stand 69), and 2.7 m (upper canopy in both stands). The work was carried out from 8 to 15 September 1995 in stand 69 and 12 September 1996 in stand 50, under overcast sky conditions and still air to avoid overexposed region around the sun and to reduce reflections on leaves. Exposures were determined by measuring sky light from the zenith region at a nearby clearing, with two stops above the reference value (i.e. overexposed by two stops). Negatives were carefully processed according to manufacturer's standards. Negatives were digitized into a 512 × 512 matrix, using a Panasonic® CCD (Charged Coupled Device) camera equipped with a 55 mm Micro-Nikkor® lens, and connected to a Cyclope® graphic board within a computer. A special program, developed by Baret *et al.* (1993) was adapted by Folmer and Walter to correct for the orthographic projection of the lens. Gap fraction data (range: 0–1) were derived by dividing the projected hemisphere into sectors of 5° zenith angles and 15° azimuth angles. Owing to the strong compression of the hemisphere near horizon by the orthographic geometry of the

Table 1. Measurement data of two Scots pine stands at Haguenau forest, Alsace, France.

Stand	Age (years)	Height (m)	Density (stems ha ⁻¹)	Basal area (m ² ha ⁻¹)
Stand 50				
<i>Pinus sylvestris</i>	80–85	30	379	24.8
<i>Picea excelsa</i>	–	25	374	6.1
<i>Fagus sylvatica</i>	–	20	68	2.0
Other species	–	20–25	21	0.5
Total	–	–	842	33.4
Stand 69				
<i>Pinus sylvestris</i>	45–50	20–25	422	20.7
<i>Fagus sylvatica</i>	–	3–6	47	0.2
Total	–	–	469	20.9

Note: Age, from Office National des Forêts (Division de Haguenau). Height, density and basal area for trees dbh ≥ 0.1 m, from original measurements at the photosites, using Cottam and Curtis centred point-quadrat method (Mueller-Dombois and Ellenberg 1974, Krebs 1999).

lens, the four 5°-wide annuli above the horizon were lumped together into a unique 20°-wide annulus. Thus, a range from 0° to 90° zenith angles was considered for the analysis. A total of 167 photographs yielded gap fraction data, which were used as input to CIMES software (Walter 1999–2001). The value of 0.5 has been chosen for $G(\theta)$, assuming a spherical distribution of foliage angles. Gap fraction data have been fitted directly to the exponential function. LAI was neither adjusted for clumping, nor for separating non-photosynthetic surfaces and species. It represents, therefore, an effective LAI.

4. Results

4.1. Vertical structure

4.1.1. Canopy openness and canopy cover

Canopy openness changes dramatically along vertical and horizontal directions in the forest. Table 2 displays average CO values for both stands. From these data, in stand 50, for the tree layer alone, canopy cover is 73.2%. Beneath the herb layer, it is 84.0%, a difference of only 10.8% with the former. Thus, the herb layer contributes on average $100 \times 10.8/84.0 = 12.9\%$, and the tree layer 87.1% to total plant cover. In stand 69, canopy cover is 95.9% beneath herbs, 90.2% beneath shrubs, and 88.2% beneath the forest roof. The herb layer contributes 5.9%, the shrub layer 2.1%, and the tree layer 92.0% to total plant cover. These results indicate that even in Scots pine stands, well-known for their relatively light canopies, the tree crowns are likely to intercept most of the incoming solar radiation (Berbigier and Bonnefond, 1995).

Variability of CO, hence CC, is shown in table 2 and in figure 1 (a and c). For stand 50, extreme values of CO show differences of 31.0% beneath the herb layer and 38.0% beneath tree crowns. Similar observations can be made for stand 69,

Table 2. Statistics summary of leaf area index (LAI) and canopy openness (CO) in two-layered (stand 50), and three-layered (stand 69) Scots pine stands at Haguenau forest, Alsace, France.

Stands	Beneath herbs		Beneath shrubs		Beneath trees	
	LAI	CO(%)	LAI	CO(%)	LAI	CO(%)
Stand 50						
Mean	2.33	15.98	–	–	1.48	26.79
SE ^a	0.35	1.37	–	–	0.28	1.57
CV(%) ^a	88.15	50.14	–	–	110.56	34.12
Median	1.57	17.86	–	–	0.98	28.73
Min.	0.80	0.78	–	–	0.58	1.91
Max.	11.02	31.75	–	–	8.36	39.89
<i>n</i>	34	34	–	–	34	34
Stand 69						
Mean	3.56	4.11	2.47	9.78	2.09	11.76
SE	0.21	0.46	0.22	0.71	0.07	0.60
CV(%)	33.30	63.43	50.83	42.53	19.70	29.28
Median	3.32	3.18	2.21	9.71	2.14	11.27
Min.	1.87	0.69	1.32	1.30	1.18	7.1
Max.	6.76	11.99	8.22	17.41	2.77	20.59
<i>n</i>	32	32	34	34	33	33

^aStandard error, and coefficient of variation (%).

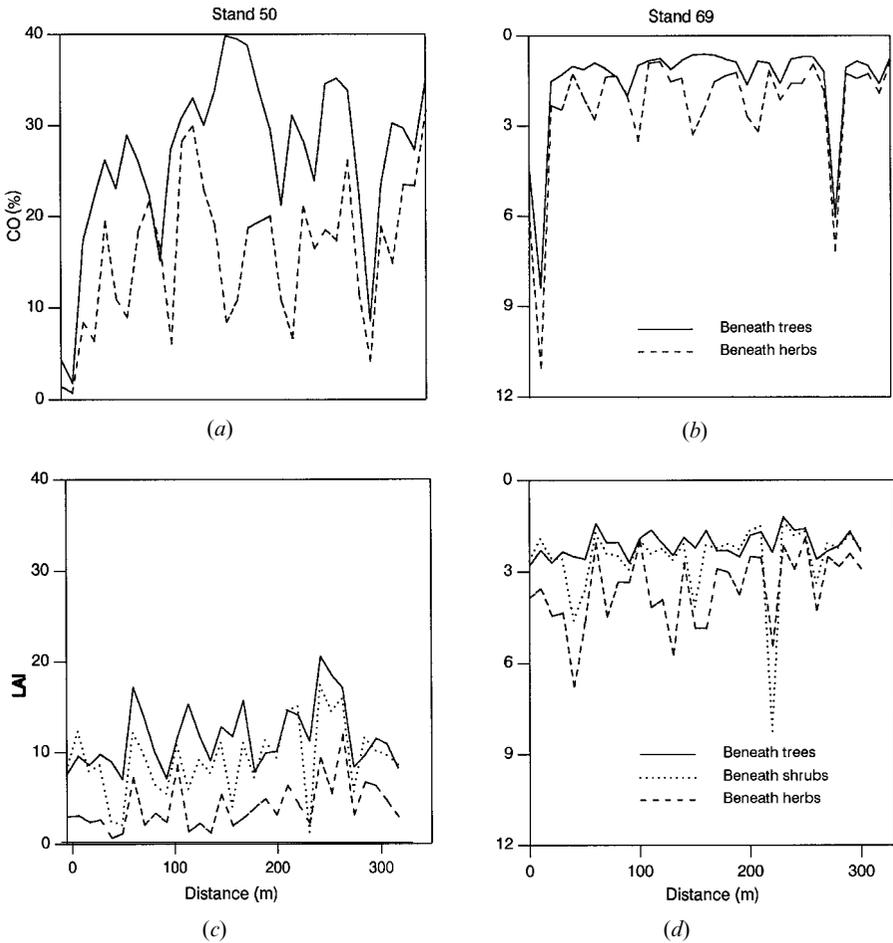


Figure 1. Horizontal and vertical variability of canopy openness. CO%: (a) and (c). Leaf area index: LAI: (b) and (d). For LAI, zero is the top of the canopy.

where CO displays differences of 11.3% beneath the herb layer, 16.1% beneath the shrub layer, and 13.5% beneath the tree crowns. In both stands, coefficients of variation decrease strongly from the herb to the tree layer, emphasizing again contrasts in patchiness among and between layers.

CO, hence CC, can be derived not only from the whole hemisphere as in the previous paragraphs, but also from selected angles. For example, figure 2 represents the variation of CC for the tree layer as a function of zenith angle. As expected, variability of CC decreases steadily as one moves from zenith to horizon. This decrease is explained by a foliage more and more dense and a distribution of gaps more and more regular from zenith to horizon. For example, in stand 50, for a zenith angle 10° (FOV = 20°), the mean CC is $29\% \pm 6$ (CV: 109.9%); for a zenith angle 25° (FOV = 50°), CC is $37\% \pm 4$ (CV: 67.9%). In stand 69, values are $53\% \pm 3$ (CV: 36.8%), and $59\% \pm 2$ (CV: 16.9%), respectively. Values for a 20° of FOV are closest to the 'nadir view' from the satellite.

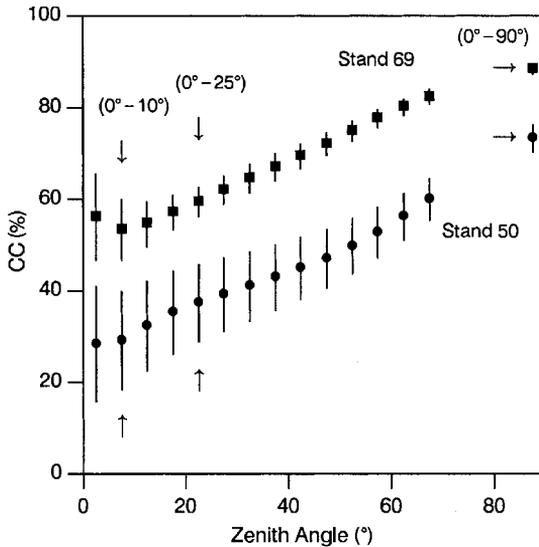


Figure 2. Canopy cover (CC%) profile of the tree layer in two Scots pine stands in function of zenith view angle. Each symbol is a mean. Vertical bars are standard errors (SE scale $\times 2$; $n=34$, stand 50; $n=33$, stand 69). Vertical arrows: values for zenith view angles $0^\circ-10^\circ$, $0^\circ-25^\circ$. Horizontal arrows: values for the whole hemisphere. Values are cumulative from left to right.

4.1.2. Leaf area index

Mean LAI values are shown in table 2. For stand 50, averages are low. Leaf area index of the herb layer is estimated to 0.9 (maximum 2.7), a contribution of 37% to total LAI. For stand 69, mean values are higher. LAI of herbs is estimated to be 1.1 (maximum 3.1), that of shrubs 0.4 (maximum 2.1), that of trees 2.1 (maximum 2.8), thus each contributing 31%, 11%, and 58%, respectively, to total LAI. In summary, undergrowth contributes as a whole 37% for stand 50, and 42% for stand 69 to total LAI.

Table 2 and figure 1(b and d) display LAI variability among and between sites. For stand 50, LAI values range from 0.8 through 11.0 above ground, and from 0.6 through 8.4 beneath trees. Moreover, coefficients of variation are much higher for LAI than for canopy openness. This result seems surprising, since LAI is known to be a 'smeared variable' (Graetz 1990), which tends to smooth out variations in gap spatial dispersion. Such a high LAI variability is strongly influenced by local dense vegetation (figure 1(b)), where LAI is probably overestimated. For stand 69, LAI values range from 1.9 through 6.8 above ground, from 1.3 through 8.2 above herbs, and from 1.2 through 2.8 (difference 1.6) above shrubs. The coefficients of variation are lower than for canopy openness beneath herbs and trees as expected, but higher beneath shrubs. High LAI values are found within the shrub sub-canopy, some of them probably overestimated.

The understory is likely to be dense beneath an open upper canopy. In other words, the higher the CC of the trees, the lower the LAI of the undergrowth. Such a negative correlation appears on a few photosites in stand 50, e.g. at 60 m, 150 m (a glade covered by a dense *Molinia* carpet), 210 m, and 250 m (figure 1(b)). However, over the whole transect, the correlation between CC of the tree layer and LAI of the

herb layer is neither negative nor significant, whether using FOV = 180° (Kendall's $\tau = 0.005$, $P = 0.965$, $n = 34$), FOV = 50° ($\tau = 0.089$, $P = 0.458$) or FOV = 20° ($\tau = 0.080$, $P = 0.505$). In contrast with the above, LAI values from herb and tree layers are well positively correlated ($\tau = 0.337$, $P = 0.005$). These observations suggest that the spatial structure of the herb layer relies not only on the actual light filtered through the trees, or on the actual struggle for water and nutrients in the rhizosphere, but more on the history of the stand. The stand is known to have suffered a heavy thinning one year before the photographs were taken. The herbaceous layer has a delayed response to such a management impact, and adjusts gradually to the new conditions. Stand 69 shows a more complex structure. The correlation between undergrowth LAI and tree layer CC was weak. It was significant only for 20° and 30° of FOV: τ was 0.316 ($P = 0.013$) and 0.260 ($P = 0.040$), respectively. Again, the correlation of LAI values between layers is relatively high: $\tau = 0.660$ ($P = 0.000$) between herb and shrub layers, $\tau = 0.540$ ($P = 0.000$) between shrub and tree layers, and $\tau = 0.407$ ($P = 0.001$) between herb and tree layers. These results are not surprising, since the stand has not undergone any recent environmental event, allowing a mixture of shade tolerating species and shade intolerant species to co-occur.

4.2. Horizontal structure

Without considering obvious vertical differences in both stands, one may ask whether measurements are spatially auto-correlated along the horizontal gradients. Horizontal structure was analysed using the approach by Thioulouse *et al.* (1995), based on the partition of total variance into two components: local variance and global variability. Total variance of variable x (observed values) is weighted by a neighbouring matrix. Local variance is identical to the covariance between x and the difference between each point and the mean of its neighbours. Following the cited authors, global variability can be seen as the covariance between x and the mean of its neighbours. Results are summarized in table 3. They are consistent with spatial auto-correlation Geary's tests (not shown). Stands 50 and 69 are well contrasted: for stand 50, global variability is significantly higher—less for LAI than for CO at the 0.10 level—than total variance for both herb and tree strata, and for the

Table 3. Spatial auto-covariance for canopy openness (CO) and leaf area index (LAI) along transects in two-layered (stand 50), and three-layered (stand 69) Scots pine stands at Haguenau, Alsace, France. Significance level is 0.05.

Stand	CO				LAI			
	Beneath herbs	Beneath shrubs	Beneath trees	Whole canopy	Beneath herbs	Beneath shrubs	Beneath trees	Whole canopy
Stand 50								
Index ^a	0.378	–	0.667	1.045	0.259	–	0.302	0.560
P	0.008	–	0.000	0.000	0.057	–	0.053	0.053
Stand 69								
Index	–0.025	–0.071	0.297	0.201	0.016	–0.021	0.047	–0.146
P	0.467	0.576	0.031	0.230	0.389	0.938	0.329	0.540

^aThe index is close to Moran's I under the hypothesis of linear neighbouring relationships, i.e. the ratio of global variability (spatial auto-covariance) to total variance (Thioulouse *et al.* 1995). P from randomization tests using $n = 1000$ permutations.

whole canopy. In other words, these results confirm that the forest is tightly structured horizontally and vertically at the stand level. Thus, measurements are not independent at this scale. This is not surprising, since the stand includes a glade, offering the opportunity of overlap and different view perspectives of the same gaps among neighbouring photosites. Conversely, only the tree stratum in stand 69 appears to be well structured at 10-m measurement intervals, and only for CO. These findings do not rule out that structures might appear at lower or higher scales, not revealed by the present sampling interval. However, they suggest that the horizontal sampling interval was appropriate to derive statistically independent LAI estimates.

5. Discussion

5.1. Technical artefacts

The distance between the fish-eye lens and the foliage influences the measurements (Trichon *et al.* 1998). The closeness of the fish-eye lens with respect to the leaves of grass, bracken and shrubs largely contributes to the high variability noted in the understory. Leaves near the camera—and trunks as well—may modify substantially the morphology, dispersion and amount of gap, and thus contribute to extremely low CO (hence high LAI) values. Moreover, discrepancy between expected and actual values may appear in such cases. For example, in stand 69 (figure 1(b and d)), some CO values above herbs are higher than above shrubs, and some LAI values are higher above shrubs than above herbs, at the same photosite. Conversely, above the lower vegetation layer, the fish-eye lens is still far enough from the tree crowns to smooth out variations recorded from the overstory. Generally speaking, estimation errors increase conspicuously beyond LAI 5–6 (figure 3). Using the Levenberg-Marquardt method for fitting gap fraction data to the exponential function (see §2, and Press *et al.* 1992), estimation errors about LAI are calculated as the square roots of the diagonal members of the covariance matrix. In very dense canopies, numerous tiny gaps highly dispersed translate into a higher spherical

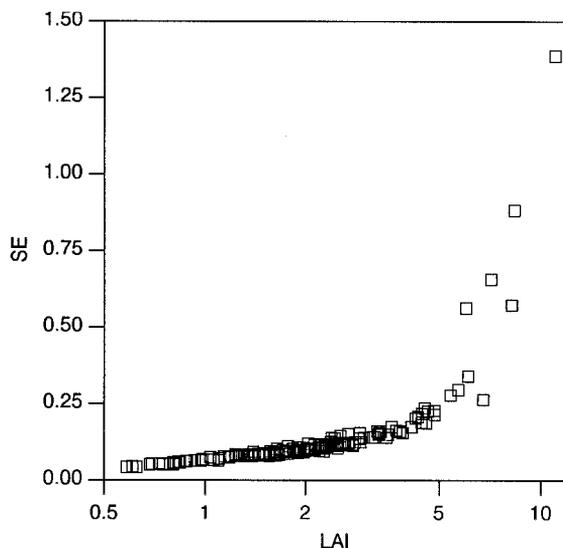


Figure 3. Relationship between standard errors (SE) of leaf area indices and LAI estimates. Kendall's correlation coefficient $\tau = 0.886$ ($P = 0.000$, $n = 167$). Each symbol is a photosite.

variance than in more open canopies (Trichon *et al.* 1998). Accordingly, the estimation errors are likely to increase.

5.2. Leaf area index

Many studies have demonstrated that optical methods tend to underestimate true LAI using the conventional Poisson model. The underestimate may be particularly critical for conifers, if correction for clumping is not applied at the shoot, branch and tree-canopy levels (Deblonde *et al.* 1994, Stenberg *et al.* 1994, Chen, 1996, Fournier *et al.* 1997, Kucharik *et al.* 1999, Gower *et al.* 1999). Fish-eye sensors do not allow direct analysis of clumping at the shoot level in conifers. Shoot silhouette-to-total-area-ratio (STAR, see Stenberg *et al.* 1994), or the variant needle-to-shoot-area-ratio (γ_e , see Chen 1996), need to be determined independently.

Hemispherical photographs nevertheless provide simple means to correct for clumping at least at the tree/canopy level for improved LAI estimates. For example, the 'logarithmic averaging method' (also known under the term 'finite length averaging method'), based on the contact number and G -function approach (Lang and Xiang 1986, Lang 1987), is easy to implement in analyses of hemispherical photographs. Details can be found in Soudani (1999) and Soudani *et al.* (2001). These principles were applied (Walter 1992, unpublished) to a 34-year old closed Scots pine stand at Hartheim, Bade-Württemberg, Germany, where Heiderich (1989) found LAI=3.8 on a projected basis, using a destructive direct method. Thirty-three hemispherical photographs were taken in the same stand. Using the Poisson model as in the present study, a mean effective LAI= 2.8 ± 0.1 (SE) was found, 75% of the Heiderich assessment, giving therefore a clumping coefficient $\Omega_e = 2.8/3.8 = 0.74$ at the canopy scale. In addition, the logs of gap fractions linearly averaged within azimuth sectors 180°, 120°, 90°, 60°, 45°, 30° and 15° in width, were computed. As log of zero is undefined, an arbitrary value ε , say $\varepsilon = 0.002$, in place of $P_0(P, \varphi)$ was assigned uniformly to each obstructed portion of the hemisphere (i.e. 1/512, the resolution of the image in pixels), a common practice (Planchais and Pontailier 1999, Gardingen *et al.* 1999). Thus, the log averaging method yielded a mean LAI= 3.8 ± 0.1 for 60°-wide sectors (four times the elementary 15° azimuth width), the closest agreement with Heiderich assessment.

Although no reference measurements were made available from Haguenu stands, the logarithmic averaging method has been experienced for the tree layer, as a guess. No ε was assigned to obstructed sky sectors. Thus, for stand 50, the highest mean (LAI= 1.6 ± 0.1) was found for 30°-wide sectors, to be compared with 1.5 ± 0.3 (table 2). Similarly, for stand 69, the highest mean (LAI= 2.7 ± 0.1) corresponded to 45°-wide sectors, to be compared with 2.1 ± 0.1 (table 2). Using the logarithmic averaging method, these results show that estimates from the logarithmic averaging method tend to be higher than those from the linear averaging method (6.7% for stand 50, and 28.6% for stand 69). Thus, although the logarithmic averaging method may be considered as an improvement over the traditional linear averaging method, no general rule can be formulated as to the 'best' azimuthal resolution if no reference measurement is available. For Hartheim stand, the 'best' estimate was determined a posteriori.

Although the discussion was limited to the tree layer, the objective of the present study was not to approximate the 'true' LAI for each layer. This would have needed to take into account the specific architecture of conifer shoots, broad leaves of shrubs and grass/fern leaves. Our interest was focused on spatial variability, relative contribution of each vegetation layer, and the role of overstory in the extent and development of the understory, from a remote sensing perspective.

5.3. Canopy cover

Canopy cover is most often quickly and subjectively appreciated visually in ecological research, looking upwards around the zenith. More rarely, it is measured on crown maps. Kucharik *et al.* (1997) used a multiband vegetation imager (MVI) to measure zenith gap-size distribution and, therefore, determined canopy cover in boreal forests. Chen *et al.* (1999) used the first annulus (FOV: 0–15° about zenith) of the PCA LAI-2000 to measure canopy cover in boreal forests. For example, they obtained on average 37% from 10 jack pine sites in Saskatchewan and Manitoba, Canada (BOREAS project). These authors directly used gap fractions in order to assess their canopy cover values, without normalizing them to the sky hemisphere. Hemispherical photographs provide a reliable mean to measure canopy cover to every direction. Using a FOV of 15° yielded a mean 32% CC in stand 50, and 54% in stand 69, for the tree layer. For a FOV 25° about zenith, CC were 37% and 59%, respectively. Spanner *et al.* (1990) studying temperate conifer forests over a wide variety of sites and forest types of the western United States, reported canopy cover values of 25–90%, based on ground-based ocular estimates and aerial photograph interpretation. In bands 3, 4 and 5 of TM data corrected for atmosphere, these authors clearly demonstrated that radiance of understory (grass, brush) was higher than from the conifer overstory (their figure 4). For conifer stands with LAI \approx 7–8, red radiance increased consistently as canopy cover decreased from 75% to 35%. Only for stands with canopy cover >89% was the relationship between LAI and band 4 radiance linear and strongly positive. With more open stands exhibiting highly reflective understory vegetation contributing to the increased infra-red response, this relationship breaks down. However, in relatively open old growth stands the integrated spectral response was strongly influenced by the presence of shadow, which lowered the radiance in both bands 3 and 4. In conclusion, several techniques are available to determine forest canopy cover, which need to be defined precisely for valid comparisons. All of them, however, provide useful information on vertical canopy stratification, which plays an important role in the integrated spectral response of vegetation for remote sensing applications.

6. Conclusion

Leaf surface area and canopy cover are well known to play an important role in the integrated spectral response of vegetation. Hemispherical photographs provide a straightforward and reliable method to characterize these forest structure attributes in three-dimensional space. In particular, the relative contribution of overstory-understory to whole canopy structure is steadily measured. Our conclusions regarding the effect of stratification on effective LAI and CC distributions can be summarized as follows:

- (1) The understory contributed 37% (stand 50) and 42% (stand 69) to total LAI in the pine forest, a non-negligible amount.
- (2) Positive correlation for LAI among layers suggest in one case a response lag of the undergrowth to a recent thinning event (stand 50), in the other case an invasion of shade-tolerant species beneath a dense tree layer (stand 69).
- (3) Canopy cover within 10° and 15° about zenith was significantly correlated with LAI (stand 69); weak and non-significant correlation between LAI and CO, hence CC, for the whole range of angles explains by the high variability size and spatial dispersion of gap.

- (4) Horizontal spatial auto-covariance among LAIs was not significant, suggesting statistical independence of these measurements; however, spatial auto-covariance of CO, hence CC, was highly significant for each layer in stand 50, but was significant only for the tree layer in stand 69.

These results emphasize the flexibility of the method to adjust for the view geometry of satellite data, particularly in respect to canopy cover. Part of the background—grasses, shrubs, and trees—recorded by airborne or satellite sensors through the forest roof from a common nadir angle, can be evaluated by hemispherical photography. Future methodological improvement with respect to the plant component of the background relies on the assessment of the bark surface, which in open and old growth stands may represent a non-negligible part of the integrated spectral response of the whole canopy.

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