BIOLOGIA PLANTARUM 43 (4): 537-544, 2000

Test of accuracy of LAI estimation by LAI-2000 under artificially changed leaf to wood area proportions

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Abstract

The accuracy of *LAI-2000* Plant Canopy Analyzer for leaf (LAI) and plant (PAI) area indexes measurements was tested in 20-year-old Norway spruce stand using the reduction of canopy biomass. Needle and branch areas were reduced progressively upward every one meter. Values of effective leaf area index (LAI_e), as an uncorrected product of *LAI-2000*, were compared with directly estimated LAI and PAI values after each reduction step. *LAI-2000* underestimates PAI and LAI values according to *LAI-2000* rings readings, and varied proportions between leaf and wood areas. The values of LAI_e have been increased with decreasing of the view angle of the relevant *LAI-2000* rings. Therefore, the underestimation of LAI becomes smaller when the readings near the horizon are masked. More accurate results, for projected LAI (LAI_p) calculation, are produced by *LAI-2000* when some dense grids of measurement points and the most vertical ring readings (0 - 13 °) are used. Correction factor 1.6 is possible to use for unreduced canopy hemi-surface LAI estimation, when the last rings (*i.e.* 5th and 4th rings, 47 - 74 °) are excluded. Correction factor of 1.25 can be used to compute LAI_p if the angle readings under 43 ° are also masked.

Additional key words: leaf area index correction factor, Norway spruce, *Picea abies*, specific leaf area, specific branch area.

Introduction

LAI is strongly dependent on canopy structure. Canopy structure includes the size, shape, orientation, and the spatial distribution of various plant organs such as leaves, stems, branches, flowers, and fruits (Norman and Campbell 1989). Recently, much emphasis has been devoted to the interpretation of the results of LAI, estimated by indirect methods. One problem of the LAI definition is its non-uniformity. The second problem arises because instruments for indirect LAI estimation assume that the leaves are small, randomly distributed, and azimuthally randomly oriented within a certain canopy volume, but these presumptions are unrealistic. Therefore, effective LAI (LAI_e) values, as a product of optical instruments, overestimate or frequently underestimate real values of LAI, especially in coniferous canopies. Thus, some correction factors of LAI_e are needed (*e.g.* Gower and Norman 1991, Fassnacht *et al.* 1994, Stenberg 1996).

Clumping effect of needles on shoot level plays the most important role on accuracy of measurement in the case of high leaf/wood area ratios (*e.g.* Stenberg 1996, Smolander and Stenberg 1996). The aim of this paper is to show the accuracy of the optical instrument *LAI-2000*, Plant canopy analyzer (*LI-COR*, Lincoln, USA), for LAI

Received 14 January 2000, *accepted* 11 May 2000.

Abbreviations: β - correction factor, Ω_E - element clumping index, BA_p - projected branch area, BA_t - total branch surface area, BAI - branch area index, LA - spherically projected needle area, LA_p - projected needle area, LA_t - total needle surface area, LAI - (hemi-surface) leaf area index , *LAI-2000* - *LAI-2000* Plant Canopy Analyzer, LAI_e - effective leaf area index, LAI_p - projected leaf area index, LAI_t - total (all sided) leaf area index, PAI - plant area index, SA_t - total stem surface area, SAI - stem area index, SBA - specific branch area, SLA - specific leaf area, SPAR - shoot silhouette to projected needle area ratio, SSA - spherically projected shoot area, SSAI - shoot silhouette area index, STAR - spherically averaged shoot silhouette to total needle area ratio.

Acknowledgements: Thanks for the provided help about this work by my former colleague Magda Opluštilová, and to some student colleagues of Heather A. Paton and Veronika Hlaváčová. Likewise, thanks for the corrections of my colleagues Otmar Urban, Jack Brossaud, and Matthew Upton. This work was supported by the grants no. 522/96/1106 and no. 205/99/1561 of the Grant Agency of the Czech Republic.

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estimation in a Norway spruce stand under artificially changed leaf/wood area proportions. Moreover, the vertical distribution of the specific leaf (SLA) and branch (SBA) areas, the leaf area index, and the branch area index (BAI) of different needle and/or shoot age classes within the canopy are also presented.

Theory

LAI definitions and methods of LAI estimation: Leaf area index quantifies the amount of assimilatory apparatus in a plant canopy. It is commonly defined as leaf area per unit area of ground. The definition varied by using the following leaf or needle area expressions: *1*) projected needle area per unit area of ground (projected LAI - LAI_p, *e.g.*, Monteith and Unsworth 1973), *2*) half of the total needle surface area per unit ground surface area (hemi-surface LAI - LAI, *e.g.*, Watson 1947, Chen *et al.* 1991, Chen and Black 1992b), *3*) total needle surface area per unit area of ground (total LAI - LAI_t, *e.g.*, Larcher 1995, Perry *et al.* 1988). The unit area of ground represents the whole forest stand ground surface area or the part of forest ground shaded by individual tree crowns.

Leaf area index can be measured or estimated using many experimental methods, which can be separated into four groups: *1*) direct methods, *2*) semi-direct methods, *3*) indirect methods, and *4*) subjective-evaluation methods. Methods and instruments for LAI estimation were reviewed in detail (see Norman and Campbell 1989, Welles 1990, Opluštilová *et al.* 1995, Pokorný and Opluštilová 1999). The main differences between individual methods can be found in the accuracy, in the possibility of repeated measurements in the same group of trees or stands, in the conditions, and in the rate of LAI estimation.

Effective LAI and correction factors: Many authors referred that optical instruments often underestimate leaf area index, especially in coniferous stands, and produce effective leaf area index (LAI_e) (Black *et al.* 1991, Chen *et al.* 1991) or shoot silhouette area index (SSAI) rather than LAI (Gower and Norman 1991, Fassnacht *et al.* 1994, Stenberg 1996). LAI_e can be defined as βLAI, where β is a correction factor called stand clumping index (Chen *et al.* 1991), shoot shading factor (Stenberg 1996) or dispersion coefficient (Baret *et al.* 1993). The value of $\beta < 1$ means that the canopy is clumped, $\beta = 1$ means that the canopy has a random leaf distribution, and $\beta > 1$ indicates that the canopy is sparse. Potential sources of errors in LAI_e estimation are: *1*) a nonrandom leaves distribution, and *2*) an influence of other shading elements (Black *et al.* 1991, Chen and Black 1991, Chen *et al.* 1991, Smith *et al.* 1993, Smolander and Stenberg 1996, Stenberg 1996). Thus, the β correction factor consists from two components related to the above mentioned errors: *1*) within shoot clumping (quantified by shoot silhouette to needle area ratio, *e.g.* Norman and Jarvis 1975, Oker-Blom and Smolander 1988, Gower and Norman 1991, Fassnacht *et al.* 1994, Stenberg *et al.* 1994, Stenberg 1996), and *2*) clumping in a scale larger than the shoot (element clumping index, *e.g.*, Ω_E, Chen and Black 1992a,b, Chen and Cihlar 1995a,b). Chen (1996) showed that Ω_E relates to the solar zenith angle. The clumping index increased with an increase of solar zenith angle; this appears because coniferous trees consist from branches grouped in distinct whorls at different heights. The crowns appear solid with small gaps around the center, but as the view zenith angle increases to near the horizontal direction, the gaps break down into whorls or branches.

The Miller's theorem (1967) proved the way how to obtain an average value of Ω_E. This is necessary because Ω_E is not constant and because the "penumbra" effect occurring on small gaps. However, the tree crowns are the major clumping structures and large gaps are critical for the Ω_E calculation.

Estimations of correction factors: The correction factors including the clumping effect of needles on shoots are mostly based on the estimation of the spherically projected areas (*e.g.*, STAR, Stenberg 1996). The total surface areas of needles or shoots are often recalculated from the projected area using a conversion factor. The surface area of needle-shape leaves averages about 2.5 times the projected area; these range from 2 for flat leaves to 3.14 for these ones with a circular cross-section (Waring 1983). For example, Johnson (1984) established the mean conversion factor for six different pine species that equals to 3.0 ± 0.28. Chen *et al.* (1991), Chen and Black (1992a) multiplied the projected needle area by the factor of 1.18 to obtain half of the total needle area for Douglas-fir trees (*i.e.* 2.32 to obtain total surface area). It is possible to use the mean value of 2.57 for Norway spruce trees (Waring 1983, Pokorný and Šalanská, unpublished data).

The most simple correction factor, including the clumping effect of needles on shoots, is SPAR (shoot silhouette area to projected needle area ratio), where only orthogonal projections onto the horizontal area of detached needles and shoots are needed. The estimation of the projected leaf area index for coniferous stands was done by multiplying the LAI_e by the correction factor R (projected needle area to average projected shoot area ratio) according to Gower and Norman (see instruction in the Manual *LAI-2000*). To calculate the total surface area index, the usage of an appropriate conversion factor is recommended (Gower and Norman 1991). The *LAI-2000* estimates directly the spherically projected area of shoots in coniferous canopies.

Stenberg *et al.* (1994) showed that the *LAI-2000* estimation represents the shoot silhouette area index (SSAI) that equals to βLAI, where the shoot shading factor β is the ratio of a spherically projected shoot area to a spherically projected needle area (β=SSA/LA or β=4STAR). The relationship between the total surface area and the spherically averaged area is based on one of Cauchy's theorems stating that, if the body of a convex shape is projected spherically, the average projected area equals to one fourth of its total surface area (Lang 1991). However, the *LAI-2000* estimates the half of the total shoot area then a correction factor, which depends on LAI definition, equals to the ratio of leaf area (projected or hemi-surface or total) to hemi-surface shoot area. Shoot shapes and appropriate correction factor in the vertical profile of the canopy varied following changed leaf/wood area proportions. It is possible, on the above mentioned assumptions basis, and on the basis of different needle/shoot age classes proportions, to evaluate some more accurate correction factors (Pokorný, unpublished data).

Correction factors can be commonly derived from the known shape, orientation, position of each canopy element, and from the known viewing direction (Lang 1991, Chen *et al.* 1991, Stenberg 1996). A practical determination is based on the comparison of direct and indirect measured LAI's (Gower and Norman 1991).

Materials and methods

Experimental plot: Measurements were carried out in the late summer 1997 in a rectangular experimental plot (Fig. 1), situated within a 20-year-old (total age of trees) Norway spruce (*Picea abies* [L.] Karst.) stand on the Experimental Ecological Study Site Bílý Kříž (Czech Republic, 49° 30' 10'' N, 18° 32' 20'' E, 908 m a.s.l.) in the Beskydy Mts. (see Kratochvílová *et al.* 1989 for detailed information).

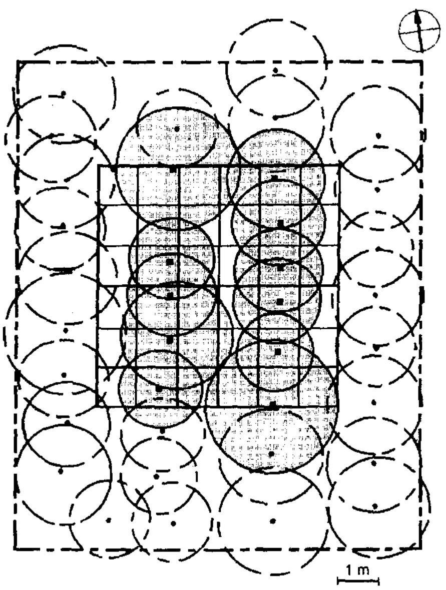

Fig. 1. Experimental plot with the location of trees and measurement points in the central grid. Eleven inner trees are printed by a gray colour. Crown projections are schematic on the basis of the mean branch length in the live crown bottom.

The trees were planted in north-south oriented lines with a 13° average descending slope following the southern direction. There were 37 trees in the experimental plot (12 × 10 m). In the center of this plot (6 × 6 m) 11 "inner" trees were marked for more detailed measurements. Stand density was approximately 3100 stems per ha. Mean tree height and stem diameter at the breast height were 7.0 ± 0.2 m and 8.4 ± 0.4 cm, respectively. The mean dimensions of the tree crowns were 6.5 ± 0.5 m in height and 2.5 ± 0.2 m in diameter (*i.e.* the crown ratio was 5.2 ± 0.2).

Structure analysis: Initially, shrubs and dead branches below the live crown (*i.e.* the branches growing less than 0.5 m above the ground) were removed from the experimental plot. After the first LAI_e measurement, the needle and branch areas were gradually reduced and LAI_e was measured. The reduction of both branch and needle areas was done in several steps by removing all branches in one meter high sections from all trees (upward from the bottom of the live tree crowns). The two whorls appeared within one section approximately. Branches above the sixth section (*i.e.* higher than 6.5 m above the ground) were separated into two sections, but they were removed in the same reduction step. Eliminated branches of each section were collected together and subsequently dried.

Eleven inner trees were harvested for a more detailed analysis of their biomass structure. A branch sample of mean length was chosen from every inner tree at each section. The sampled branches were cut and split into three age classes of shoots (c - current, c-1 - one year old, and r - rest; *i.e.* the older parts of the branch) for the assessment of these following main structural parameters: specific leaf area, specific branch area, dry needle and branch mass, projected needle area, and total branch area.

The percent representations of individual age classes in the total branch biomass were calculated and then used for the determination of the dry weight and surface area of corresponding needle/shoot age classes within the whole section. All stems were removed from the experimental plot and a final measurement of LAI_e was done to check an eventual edge effect of the surrounding stand at the end of the experiment. In addition, the surface areas of all stems were obtained using the Huber's method (*e.g.*, Korf *et al.* 1972).

Direct evaluation of LAI: Some randomly chosen shoots of the three needle age classes (c, c-1, r) from sampled trees in the eight vertical canopy layers were used for the evaluation of the specific leaf area (SLA; a ratio between fresh projected area of needles to their dry mass [cm^2 g^{-1}]). A fresh projected needle area was measured by the *LI-3000A* Portable Area Meter (*LI-COR*, Lincoln, USA). The projected needle area (LA_p) of needle age classes within a whole section was calculated from the known amount of dry needle biomass and the SLA on the basis of all age classes and their mass proportions within the sampled branches. The mean values of SLA for the relevant age class/section were used for the calculation of the projected leaf area of all the trees around the inner ones within each section. The total needle surface area (LA_t) was established when LA_p was multiplied by the conversion factor of 2.57. The values of the directly estimated LAI were then obtained as a ratio of the certain leaf area (half of total) of the canopy sections to the stand surface area.

Direct evaluation of BAI: Similarly, the total branch area (BA_t) was estimated using the specific branch area (SBA; total branch surface area related to its dry mass ratio). A surface branch area was calculated from the known lengths and diameters of the shoots. The SBA was calculated on the basis of dry biomass of all the woody parts of detached shoots from the sampled branches. The BA_t for all the other trees in the experimental plot was then recalculated from each section for the average SBA and the known dry branch biomass of each canopy section. The projected area of branch (BA_p) equals to the BA_t divided by π. Branch area index (BAI) is defined as a ratio between hemi-surface branches and stand surface areas.

Direct evaluation of SAI: The total surface area of each stem (SA_t) was estimated by Huber's method from the known length and stem diameter measured in the middle part of each section. Each section was assumed to be of a cylindrical shape. Stem area index (SAI) is defined as the ratio of the sum of all hemi-surface stem areas to the stand area.

***LAI-2000* measurement:** The optical detector of the *LAI-2000* is composed of different sensors, arranged as five concentric rings, that measure diffuse blue radiation (400-490 nm) in different view angles (0 - 13 ° - 1st ring, 16 - 28 ° - 2nd ring, 32 - 43 ° - 3rd ring, 47 - 58 ° - 4th ring, and 61 - 74 ° - 5th ring). This allows to compute radiation transmission and estimation of LAI in a forest canopy. Scattering of blue radiation in the stand is negligible. The ratio of each ring above-and-below-canopy radiation value refers to the canopy gap fraction for each detector (Gower and Norman 1991).

Below-canopy measurements with the *LAI-2000* were made about 0.3 m above the ground in a grid of 6 × 6 m at 1 m intervals (*i.e.* 49 measurement points). Above-canopy readings were taken before and after measurements of all fixed points, in a free place nearby the stand. Measurements were repeated at least three times after each reduction step. The 90 ° view restrictor was used in all measurements to exclude the operator from the viewing area. All readings were approximately taken at the sunset or sunrise times, under clear sky conditions, showing low and slowly changing radiation results. The calculation of LAI from the *LAI-2000* measurements was done by a PC program *C2000*.exe (*LI-COR*, Lincoln, USA) using an interpolation of all above readings. All effective values of LAI were recalculated with masking of different rings.

Results and discussion

Directly evaluated LAI, BAI, and SAI: Both specific leaf area (SLA) and specific branch area (SBA) of Norway spruce needles and shoots were dependent on the shoot age and its position within the vertical canopy profile. SLA decreased with the needle age and increased with the depth into the canopy as was observed earlier (*e.g.*, Beets and Lane 1987, Gilmore *et al.* 1995, Dvořák and Opluštilová 1995). The SBA values had similar course (Fig. 2). LAI and BAI values varied with different needle (shoot) age classes and their proportions in the vertical canopy profile as well (Fig. 3). The minimal values of LAI, BAI, and SAI were obtained in the upper part of the canopy. After that, all indexes increased continuously downward except the LAI, which decreased at the bottom of the canopy. The minimal values of LAI and BAI were obtained close to the ground surface beneath the first section (data not shown). The obtained results are in agreement with previous published data of needle area distribution in vertical profiles of coniferous canopies (*e.g.* Vose and Swank 1990, Wang *et al.* 1990, Webb and Ungs 1993, Van Hees and Bartelink 1993, Chroust 1993, Barták *et al.* 1993, Čermák *et al.* 1998). Furthermore, value of the stem surface area was small compared to the surface areas of other canopy organs until removing about one half of the canopy. Therefore, the stem surface area was taken as a constant (cumulative hemi-surface SAI = 0.19). Moreover, visible cumulative SAI beneath the crown level was smaller, and it was vertically changed (Fig. 3c). Directly evaluated LAI_p, LAI, and plant area index (PAI; PAI = LAI + BAI + SAI) data are presented together with the LAI_e data in Fig. 4.

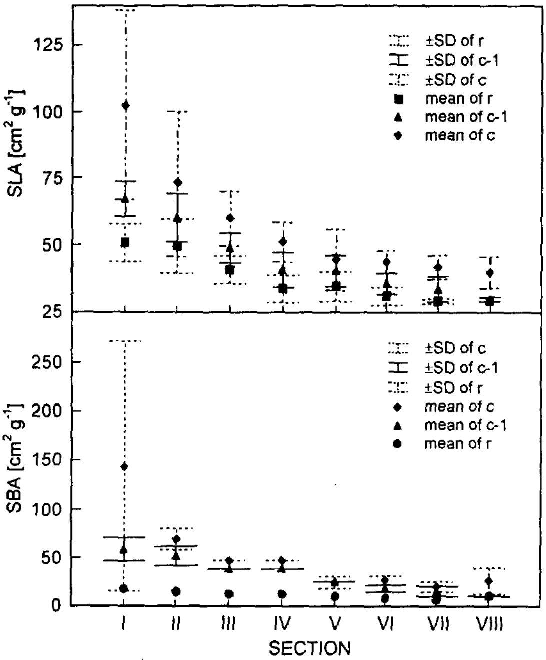

Fig. 2. Vertical SLA and SBA distributions of different needle age classes per section. c - current needles, c-1 - one year old needles, r - older needles; $n = 11$.

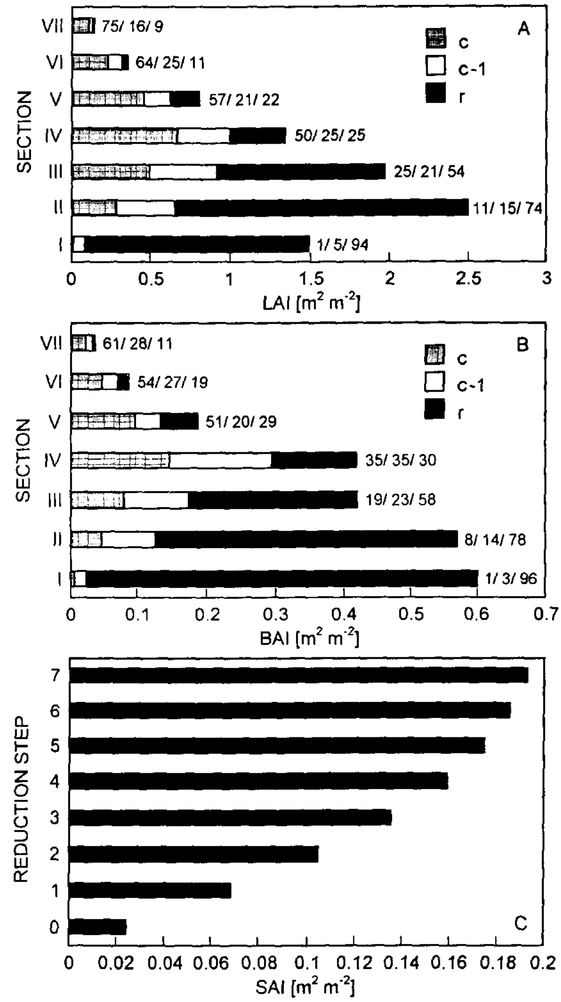

Fig. 3. Vertical LAI and BAI (*A*, *B*) distributions of different needle age classes and their percent proportions within removed section. The VIIth section represents cumulative LAI and BAI above the VIth section. c - current needles, c-1 - one year old needles, r - older needles. Cumulative SAI (*C*) beneath the crown level after each reduction step (0 - before reduction, 1 - 6 - after section removal, 7 - stems only).

Leaf/wood area proportions: The total proportions between the cumulative hemi-surface areas of leaves, branch and stem, and the area indexes, before and after each reduction step, showed a variation of leaf/wood areas proportions in the vertical profile of the canopy (Table 1). Within the canopy, the surface area of leaves is much larger (even seven times) compared with the woody parts surface areas (Table 1). Proportions between the leaf and woody areas (stems and branches together) were practically the same until the branches at about one third of the canopy height were removed. Some small decreases of these values were observed until the reduction of 36 - 64 % of the crowns. Stem surface area appears more negligible compared with the leaf and branch areas till the 64 % of crown layer was removed. Thus, rapid decrease of both leaf and branch area proportions was found after removing about three fourth of the crowns. Stem surface area proportions increased upward to 100 % after that. In addition, the minimum of the woody area proportions within the canopy ranged between 12 and 14 %.

Comparison of direct and indirect LAI and PAI evaluations: The values of LAI_e were compared with the LAI_p values, as well. The basic data of LAI_e were recalculated from different view angles, when different ring readings were covered (Fig. 4). The correction factors for recalculation of the LAI_e values to hemi-surface LAI are presented in Table 2. It is possible to obtain the projected LAI_p values, just multiplying the above mentioned correction factors by 2/2.57. Because an edge effect, the correction factors varied within the interval from full to no edge effect (Table 2). However, it is possible to define (or interpolate) an edge effect, which increased from about zero before-canopy reduction to the full edge effect. The underestimation or overestimation errors are strongly dependent on the used ring readings of the *LAI-2000* and on the wood to leaf area proportions. It is possible to see from the comparison of LAI_e with directly evaluated LAI, PAI, and LAI_p values (Table 2, Fig. 4). High statistically significant differences ($P < 0.01$, Sheffe test) were found between all values of

LAI_e when different angles of sensor views were masked, especially before and after the removal of the first section. It shows high importance of different view angles for the LAI estimation when the bottom of the canopy is relatively closed to the sensor (< 1.2 m), even if leaf/wood area proportions are relatively stable. No statistically significant differences were found between computed LAI_e values, when the first, the second, and mostly the third ring readings were used (0 - 43 °). Therefore, it is possible to recommend to cover only the last two ring readings (47 - 74 °) for the *LAI-2000* measurements if the canopy bottom is 1.2 m over the sensor. Thus, it is possible to obtain a set of recommendations when different view angles of the *LAI-2000* are used in Norway spruce stands with different leaf to wood area proportions (Tables 1, 2). The statistically significant differences of LAI_e values after each reduction step were evaluated, as well (normal-like distribution, Sheffe's test). Small variations in LAI_e measurements after each reduction step were recorded, especially when no ring reading was masked. It was difficult to distinguish the changes of LAI_e (independently on the number of masked rings) after removing the fourth canopy section (Fig. 4). The fourth section appears to be a transitional section between underestimation and overestimation of LAI by the *LAI-2000*. If LAI of the spruce canopy is smaller than 1.3 (see Fig. 3*A* - sum of the 5th, 6th and 7th section or directly Fig. 4) and if the woody area proportion is over 20 %, then the *LAI-2000* can not measure very accurate changes of LAI. This proportional border is also in an agreement with the results of Smolander and Stenberg (1996) for Scots pine stand.

The *LAI-2000* underestimates the projected plant area index (PAI_p) value of about 31 %, the hemi-surface plant area index (PAI) (48 %), the LAI_p (23 %), and the LAI (40 %) for a full canopy. The LAI underestimation corresponds with the results of Chen (1996). At the last measurement without masks, when only stems remained, the LAI_e estimation was in a good agreement with the direct measurement of the PAI, respective stem area index (SAI). Before removing the first canopy section, the data of LAI_p and LAI_e were fitted (97.5 % of accuracy), especially when only the last vertical *LAI-2000* ring readings were used. Also other authors found that the underestimation errors become greater when *LAI-2000* ring readings near the horizon view are used (*e.g.* Chen and Black 1991, Chen and Cihlar 1995b, Chen 1996).

If the proportions of woody areas are over 12 %, correction factor including the shading effect in a scale larger than the shoot is needed (Stenberg 1996). This idea is supported by results of SPAR correction factor measurements. The mean SPAR value for Norway spruce canopy was in the range of about 0.87 (Šubrtová 1994), and 0.84 (Leverenz and Hinckley 1990). Therefore, appropriate correction factor for LAI_e recalculation equals to 1.19 or 1.15 (1/SPAR). These values were well fitted as correction factors to the recalculation of LAI_e to LAI_p when the last two or even three *LAI-2000* ring readings were masked (Table 2; correction factors multiplied by 2/2.57). To compute the hemi-surface leaf area index, when the last two *LAI-2000* ring readings were masked, the correction factor ranged between 1.60 and 1.67. The identical correction factor value (1.60) for Norway spruce canopies was early presented by Gower and Norman (1991). The accurate values of correction factors under the variation of LAI and the changed leaf to wood area proportions are presented in Table 2. Vertical distributions of SPAR for different needle/shoot age classes correspond to their own proportions within a canopy would be necessary for further detailed analysis.

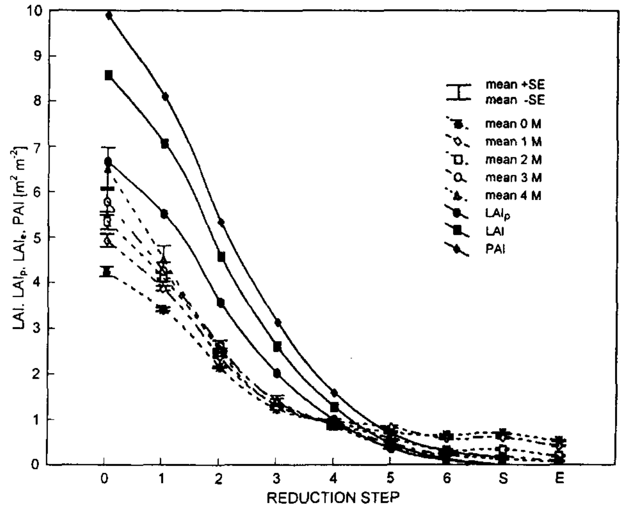

Fig. 4. The values of PAI, LAI, LAI_p and LAI_e obtained before and after each reduction step (0 - before reduction, steps 1 - 6 - after removal of the branch sections, S - when remained only stems, and E - edge effect of the surrounding forest stand). The values of LAI_e were recalculated for different angles of view (without mask - 0M, 5th ring masked - 1M, 5th and 4th rings masked - 2M, 5th, 4th, and 3rd rings masked - 3M, 5th, 4th, 3rd, and 2nd rings masked - 4M).

Conclusion: The most important concept to obtain a true LAI is not only the individual shoot clumping (Norman and Jarvis 1975, Gower and Norman 1991), but also the proportions of wood/leaf area (Smolander and Stenberg 1996, Chen 1996). From the Chen's (1996) error analysis the total error comes from *1*) the *LAI-2000* measurement, *2*) the element clumping index, *3*) the needle-to-shoot area ratio, and *4*) the woody-to-total area ratio. Moreover, Chen and Black (1991) suggested that it is better when the last two ring readings of the *LAI-2000* are removed to avoid large errors. The above presented results correlated very closely with these assumptions. In the case that the mean LAI_e of spruce canopy is larger than 0.94 (no mask) and the wood/leaf area proportion is less than 20 %, it is possible to recommend for the hemi-surface LAI estimation to use the mean correction factor 1.84 when

Table 1. The cumulative proportions between LAI, BAI and SAI after each reduction step (0 - before reduction, 1-6 - removal steps, Stems - after removal of all branches) within the rest of canopy. The relative heights of the removal sections above the ground are described as well. Wood area proportion equals to BAI + SAI.

Reduction step Height	0 0-7	1 7-21	2 21-36	3 36-50	4 50-64	5 64-79	6 79-93	Stems 100
LAI [%]	86	87	88	83	80	69	44	0
BAI [%]	12	11	10	12	10	9	6	0
SAI [%]	2	2	2	5	10	22	50	100

Table 2. The range of correction factors of the LAI_e values for conversion to the hemi-surface LAI in each reduction step are presented when the different ring readings of the *LAI-2000* are masked (without mask - 0M, 5[th] ring masked - 1M, 5[th] and 4[th] rings masked - 2M, 5[th] ,4[th], and 3[rd] rings masked - 3M, 5[th], 4[th], 3[rd], and 2[nd] rings masked - 4M). The correction factors ranged from zero to full edge effect. The same letters note no statistically significant differences, stars statistically significant differences ($P < 0.05$), in the other cases appeared some high statistically significant differences ($P < 0.01$) between the LAI_e values.

	0	1	2	3	4	5	6
0M	2.03-2.32	2.08-2.46	2.12-2.82	2.10-3.70a	1.38-3.24abc	0.68-2.61a	0.22-1.19*
1M	1.74-1.91	1.83-2.05	1.92-2.33	1.98-2.89ab	1.32-2.31*b	0.59-1.18a	0.24-0.84*
2M	1.60-1.67	1.72-1.81*	1.82-1.98a	1.99-2.35ab	1.42-1.82abc	0.81-1.21bc	0.43-1.09a
3M	1.48-1.51	1.66-1.70*	1.75-1.81b	1.86-1.99bc	1.46-1.62abc	1.01-1.24bcd	0.59-0.95ab
4M	1.32-1.33	1.57-1.60	1.79-1.85ab	1.82-1.93c	1.49-1.64*c	1.21-1.50d	0.65-1.02b

the viewing angle varied within the range 0 - 43 °. The final accuracy of the LAI estimation was then about ± 15 % (derived from the correction factor analysis, when the full - no edge effect range was accounted, Table 2). The correction factor of 1.6 presented by Gower and Norman (1991) to calculate the LAI and 1.25 to calculate the LAI_p can be used for the full canopy when the last two ring readings of the *LAI-2000* are masked. However, to obtain the most accurate results by the *LAI-2000* in Norway spruce canopies, it is better to measure in a dense grid of measurement points (less than 1 × 1 m) and to use the most vertical ring readings for both the LAI and LAI_p calculations.

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