

T. Holst · S. Hauser · A. Kirchgäßner · A. Matzarakis ·
H. Mayer · D. Schindler

Measuring and modelling plant area index in beech stands

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Abstract For some beech (*Fagus sylvatica* L.) stands with different stand densities the plant area index (PAI) was measured by means of a Licor LAI-2000 plant canopy analyser. The stands are located on the slopes of a valley in south-west Germany and had been treated by different types of silvicultural management (heavy shelterwood felling, light shelterwood felling, control plot). The analyser was used (a) to investigate the light conditions on plots of the same thinning regime, (b) to quantify the differences between the different treatments and (c) to obtain absolute values of PAI for interdisciplinary research. PAI was measured at three different phenological stages (leafless, leaf-unfolding and fully leafed season in 2000) and was found to be about 5.2 for the fully developed canopy on the control plots, 3.2 on the light fellings and about 2.0 for the heavy fellings. In the leafless period PAI was between 1.1 (control) and 0.4 (heavy felling). Measurements made in summer 2000 and summer 2002 were compared, and showed an increase of PAI, especially on the thinned plots. Measurements of photosynthetically active radiation (PAR) above and below the canopy in combination with measured PAI were used to apply Beer's Law of radiation extinction to calculate the extinction coefficient k for different sky conditions and for the different growing seasons on the control plots. The extinction coefficient k for the beech stands was found to be between 0.99 and 1.39 in the

leafless period, 0.62 to 0.91 during leaf unfolding and between 0.68 and 0.83 in the fully leafed period. Using PAR measurements and the k values obtained, the annual cycle of PAI was modelled inverting Beer's Law.

Keywords Plant area index · LAI-2000 · *Fagus sylvatica* L. · Photosynthetically active radiation · Beer's Law

Introduction

The canopy of a forest has a significant impact on the forest's microclimate. The crown layer has a strong influence on the radiation regime within a stand (e.g. Geiger et al. 1995; Baldocchi et al. 1984a, b; Hutchison and Matt 1977). In the canopy layer, part of the incident short-wave radiation is used for photosynthesis, while some radiation is transmitted through the leaves or reflected by the canopy. Since short-wave radiation is the most important energy input, this has a strong impact on air and soil temperatures, humidity levels and evapotranspiration, defining the growing conditions for the understory and the forest stand itself (e.g. Grimmond et al. 2000; Morecroft et al. 1998; Geiger et al. 1995; van Eimern and Riedinger 1986). Therefore information about the structure of the canopy of a forest is not only necessary to address micrometeorological questions, but also for the analysis of structures and processes in other disciplines like forestry, biology or soil science.

A widely used method to describe the amount of foliage is the plant area index (PAI) when referring to all light blocking elements (stems, twigs, leaves), or the leaf area index (LAI) when accounting for leaves only (López-Serrano et al. 2000; Meir et al. 2000; Nackaerts et al. 2000; Ross et al. 2000; Levy and Jarvis 1999). Though PAI and LAI are dimensionless they can be thought of as m^2 (one-sided) foliage per m^2 ground area.

For the determination of a stand's PAI or LAI, there are direct and indirect techniques: while harvesting of the whole canopy or some samples of the vegetation is destructive and laborious, taking samples of litter is non-

T. Holst (✉) · A. Kirchgäßner · A. Matzarakis · H. Mayer ·
D. Schindler
Meteorological Institute, University of Freiburg, Werderring 10,
79085 Freiburg, Germany
e-mail: thomas.holst@meteo.uni-freiburg.de
Tel.: +49-761-2033590
Fax: +49-761-2033586

S. Hauser
Institute for Forest Growth, University of Freiburg,
Tennenbacherstraße 4, 79085 Freiburg, Germany

Present address:

A. Kirchgäßner, Meteorological Institute, University of Hamburg,
Bundesstr. 55, 20146 Hamburg, Germany

destructive but also very time-consuming. Among modelling approaches (e.g. Law et al. 2001; Ross et al. 2000) including statistical and three-dimensional radiative transfer models, the use of the radiation regime below the canopy itself for the description of the crown layer is very common. For example the structure of the foliage can be analysed via hemispherical photography ("fish-eye") for specific points below the canopy, looking for gaps in the canopy layer, where direct or diffuse radiation can reach the ground. By taking various photographs at different points in the stand one can calculate a representative PAI for the stand (Frazer et al. 2001; Meir et al. 2000; Levy and Jarvis 1999; van Gardingen et al. 1999). Welles (1990) gives an overview over some of the tools for analysing PAI mostly on the basis of radiation, one of them being the LAI-2000 plant canopy analyser (Licor Inc., Lincoln, NE, USA; Welles and Norman 1991). Although the LAI-2000 instruction manual uses the expression LAI, PAI is more appropriate in this context since the sensor is measuring all light-blocking elements (Licor 1992). In this study the LAI-2000 analyser was used to measure PAI for beech canopies (*Fagus sylvatica* L.) within stands of different densities due to different silvicultural treatment. The main goal of this study was to verify whether the silvicultural treatments led to (a) comparable conditions in plots that have undergone the same degree of thinning and (b) clearly different conditions in plots with different stand densities. A second objective was to obtain absolute values of PAI for all plots.

There are a lot of studies dealing with relative irradiance measured below forest canopies including coniferous and deciduous stands (e.g. Kull et al. 1999; Dufrière and Bréda 1995; Yang et al. 1993; Rich et al. 1993; Baldocchi et al. 1984b; Reifsnyder et al. 1971), and some of them use Beer's Law to describe light extinction in the canopy layer. For canopies with almost two-dimensional extension and no deep foliage Reifsnyder et al. (1971) showed that Beer's assumption of exponential extinction is not valid and a more linear radiation extinction has to be used. Planchais and Sinoquet (1998) found similar results for beech, but they worked on the branch scale, not on a stand scale. They investigated branches from open-grown and understory saplings in different light environments (upper, middle and lower crown) and they reported that an assumption of uniform leaf area density and random leaf location was not valid throughout the whole canopy as there were differences between the sunny (more erect leaves) and shaded (more horizontal leaves) parts of the crowns. This is contrary to the theoretical assumptions (that foliage is randomly distributed and randomly oriented/inclined) for the LAI-2000. A study by Kull et al. (1999) for an oak forest in the United Kingdom showed similar results to those of Planchais and Sinoquet (1998). Leaves in the upper canopy had large inclination angles while leaves in the lower canopy showed a more horizontal orientation, both deviating substantially from random. Referring to the whole canopy layer, they concluded that Beer's Law was a reasonable estimate. As Mayer et al. (2002) reported,

exponential extinction is applicable for the stands in Tuttlingen-Möhringen on which this study is based.

Considering the annual cycle of PAI, studies of the influence of the growing season on radiation regimes below a deciduous forest canopy can be found (e.g. Rich et al. 1993; Baldocchi et al. 1984a,b), and some studies give solitary PAI measurements at certain phenological stages, but there are only a few studies on the annual cycle of PAI in forests. Leblanc and Chen (2001) presented measurements of PAI taken with an LAI-2000 plant canopy analyser on more than ten occasions throughout the growing season for a deciduous forest (70% poplar). Chason et al. (1991) made measurements with an LAI-2000 analyser throughout late summer and during leaf fall in an oak/hickory forest and compared the results to estimates from photosynthetically active radiation (PAR) measurements and litter. Gond et al. (1999) reported seasonal variations correlated to plant phenology for a temperate forest (including *Quercus robur* L.) in Belgium on the basis of LAI-2000 measurements. Litter samples or hemispherical photographs can be used instead of LAI-2000 measurements to obtain information about the seasonal variability of canopies. Neumann et al. (1989), for example, compared leaf area measurements based on leaf litter collection to hemispherical photographs in a mixed deciduous forest (aspen, maple, cherry) during autumn leaf fall while Levy and Jarvis (1999) determined LAI for the growing season for millet and fallow sites (bushes) in the Sahelian zone in Niger, deduced from direct measurements and hemispherical photographs. In addition, there are some models available that are certainly suitable for modelling the annual cycle of PAI of deciduous forests (e.g. Stadt and Lieffers 2000; Pukkala et al. 1991). Ross et al. (2000) proposed a statistical interpolation method to calculate LAI, leaf area density and other variables for any day of the growing season, elaborated using phytometrical measurements carried out in willow coppices.

In this study the annual course of PAI for two homogeneous deciduous canopies including different phenological stages could be modelled using Beer's Law (Tsubo and Walker 2002; Kull et al. 1999; Utsugi 1999; Johansson 1996) on the basis of discontinuous PAI measurements at different phenological stages and continuous measurements of photosynthetically active radiation (400–700 nm) above and below the canopy.

Forest sites

The forest sites of this research project are located on the Swabian Alb (Germany), about 100 km south of Stuttgart and 90 km east of Freiburg, on the two opposite slopes of a valley near Tuttlingen-Möhringen (48°01'N, 8°49'E; elevation 720–840 m above sea level). Since the valley's axis runs from SE to NW, one slope is exposed to the NE (NE slope) and the other one to the SW (SW slope), with an inclination of about 23–30°. The stands are mainly (> 90%) composed of beech trees (*F. sylvatica* L.) with an

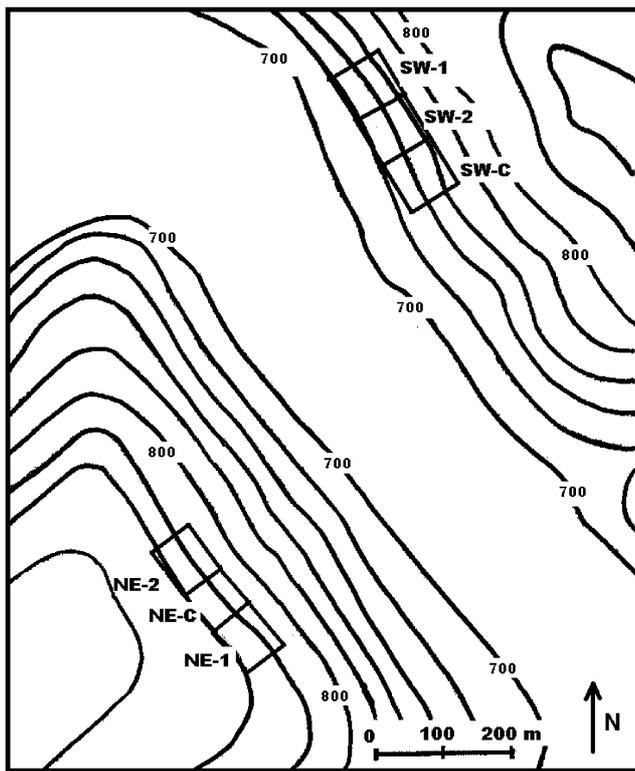


Fig. 1 Experimental sites on two opposing slopes in a valley near Tuttingen-Möhringen (Swabian Alb, Germany) with plots of different silvicultural treatment (control plot, C; light shelterwood felling, 1, heavy shelterwood felling, 2) and different aspect (NE slope, SW slope)

average age of 73 years on the NE slope and 82 years on the SW slope [as determined from tree rings taken at 1.3 m (Rennenberg 2001)]. The sites were subdivided into plots of approximately 70 m × 70 m when research started in 1999. While the control plots are not silviculturally treated, the basal area of the stands was reduced from approximately 25 m²/ha to about 15 m²/ha (light felling) and to about 10 m²/ha (heavy felling) on the silviculturally treated plots, respectively (Fig. 1). Within these units only an area of 30 m × 30 m was actually used to take measurements to minimize the effects of adjoining units with a different degree of thinning. The silvicultural treatment was a shelterwood felling, which can be thought of as a very heavy felling with some adult trees left uncut.

Table 1 Stand characteristics of the beech stands on the NE and SW slopes. C denotes the control plot, 1 and 2 the light and heavy shelterwood felling respectively. Tree heights and tree diameter $d_{1.3}$

Characteristic	NE-C no treatment, control plot	NE-1 light shelterwood felling	NE-2 heavy shelterwood felling	SW-C no treatment, control plot	SW-1 light shelterwood felling	SW-2 heavy shelterwood felling
Basal area (m ² /ha)	27.0	14.7	11.4	21.0	15.0	10.4
Tree density (ha ⁻¹)	526	254	123	576	312	199
Mean tree height (m)	26.5	27.1	31.9	21.1	23.5	22.8
Mean $d_{1.3}$ (cm)	25.6	27.1	34.4	21.5	24.7	25.8

These uncut trees serve several purposes such as giving shelter for the forest floor and protecting young trees from direct sunlight and wind, producing seed or as a potential value for harvest. Stand characteristics of the research plots are summarized in Table 1. Additional information about the investigation area, aims and instrumentation is given in Mayer et al. (2002), Rennenberg (2001), Geßler et al. (2001) and Holst et al. (2000, 2001).

Materials and methods

PAI measurements

The use of the LAI-2000 plant canopy analyser for the determination of PAI is widely reported in the literature (e.g. Law et al. 2001; Prskawetz and Lexer 2001; Leblanc and Chen 2001; Nackaerts et al. 2000; Gond et al. 1999; Pokorný and Opluštilová 1999; Dufrène and Bréda 1995; Yang et al. 1993; Chason et al. 1991). The LAI-2000 consists of an optical sensor and a computing unit. Basically, the optical sensor functions similarly to a camera with a fish-eye lens. This lens focuses radiation from a 148° field of view onto the sensor itself. The sensor consists of five concentric, light-detecting silicon rings each being responsible for a different part of the sensor's field of view. The inner ring (ring 1) responds to radiation falling from an angle between 0° and 12° (zenith = 0°), ring 2 to radiation from 17° to 29° and ring 3 to incident radiation from 32° to 43°. The outer rings 4 and 5 respond to radiation from 43° to 58° and 62° to 74° respectively. The sensors are sensitive to wavelengths above 320 nm and a filter rejects radiation of wavelengths over 490 nm to avoid underestimation of the PAI by measuring radiation transmitted or reflected by the leaves into the sensor's field of view. To reduce errors in the measurements by the user's body, which may shade part of the sensor, or by vegetation of different "optical" characteristics surrounding the measurement site, the sensor rings can be shaded with so-called view caps.

The PAI is determined by taking measurements above the canopy/outside the stand (A readings) and below the canopy/inside the stand (B readings) and calculating the difference between the incident radiation above and below the canopy. Several below-canopy readings and the fish-eye field of view ensure that PAI calculations are representative for a particular stand.

To investigate the influence of the canopy of the stands on light conditions and to measure whether the silvicultural treatment led to comparable light conditions in plots that had undergone the same degree of thinning, PAI measurements were conducted in 2000 and in 2002 by using two LAI 2000 plant canopy analysers. Measurements were taken in two-sensor mode, where one sensor takes the A readings (above canopy) and the other the B readings (below canopy) simultaneously and data are combined afterwards by means of a computer program (C2000) that calculates PAI. Since towers were not available in 2000, the above-canopy readings were taken in a meadow centered in the valley; the elevation difference from that of the forest plots was about 60–150 m. The horizontal distance to the research sites was approximately 600 m. In 2002 towers were

(measured 1.3 m above ground) are given as an average for the particular plot

used for the above-canopy readings. Below-canopy readings were conducted at a height of 1.3 m above ground on three plots on each slope, including the heavy shelterwood felling, the light shelterwood felling and the control plot. Additional measurements at a height of 3 m above the ground were conducted on the heavy shelterwood fellings in 2002 because the understory vegetation reached about 2.5 m and influenced PAI measurements at 1.3 m above ground. On each plot six below-canopy readings were registered on a transect from the SE corner to the NW corner; it was not possible to take more readings per plot because the plots are used by several scientific groups and this would have disturbed other installations. To account for the inhomogeneous conditions observed in forests – in contrast to more homogeneous conditions in crops – a reduction of the LAI-2000 sensor's field of view by means of the view caps and a larger number of individual below-canopy readings within the stem layer are required. One factor leading to errors in the calculations of PAI is in the use of a logarithmic function while for every single reading the computing unit linearly averages the gap fraction of the sensor's view (Welles and Norman 1991). Thus, including dense and sparse parts of the canopy, or including neighbouring sites with different stand characteristics in one reading, leads to wrong results. By restricting the sensor's field of view by a view cap, the user can reduce the probability of including sparse and dense parts of the canopy in one reading. The measurements at the sites near Tuttlingen-Möhringen were conducted with view caps limiting the field of view to 45° to account for the stand characteristics, especially for those of the heavy shelterwood fellings. In addition to the restriction of the field of view the measurements for each plot were repeated several times on each occasion to get more representative results. In addition, all readings of ring 5 (at 68° from zenith) were omitted to reduce the view range of the LAI-2000 for the PAI calculations (a) to avoid boundary effects of adjacent plots with different stand densities, and (b) to avoid inclusion of sections obscured by the slope (Chason et al. 1991).

Modelling the annual cycle of PAI

As part of the continuous micrometeorological measurements, PAR was measured as photon flux density ($\mu\text{mol m}^{-2} \text{s}^{-1}$; Licor LI-190, Licor Inc., Lincoln, NE, USA) 1.5 m above the ground on the heavily thinned plot and on the control plot on each slope after fall 1999. PAR and global radiation G (W m^{-2} ; CM21 pyranometer, Kipp+Zonen, Delft, Netherlands) values above the canopy were available from fall 2000 when two towers (approximately 1.5 times forest height) were installed on the control plots.

Adapting Beer's Law to describe the extinction of radiation by a homogeneous medium to the extinction by a forest canopy, one will find (e.g. Tsubo and Walker 2002; Kull et al. 1999; Utsugi 1999; Johansson 1996)

$$I = I_0 \cdot \exp(-\text{PAI} \cdot k) \quad (1)$$

where I is the incident radiation below the canopy layer, I_0 is the incident radiation above the extinguishing medium (e.g. canopy layer) and k is its extinction factor. PAI is used as unit for the optical thickness of the medium. Referring to the photosynthetically active part of the solar spectrum and solving for PAI leads to

$$\text{PAI} = (-1/k) \cdot \ln(\text{PAR}/\text{PAR}_0) \quad (2)$$

where PAR is photosynthetically active radiation measured below the canopy and PAR_0 is incident photosynthetically active radiation above the canopy layer. Since k depends on the angle of incidence, it has a daily cycle according to the elevation of the sun. Unlike k , the PAI (of beech) does not show a daily cycle but a distinct annual cycle starting with leaf unfolding in spring and ending with the loss of foliage in autumn. In 2000 PAI was identified at three different phenological stages: in the leafless period, during leaf unfolding and under full-canopy conditions. Unfortunately measurement of shortwave radiation above the canopy, necessary for the determination of the relative irradiance used in Eq. (2), only started at the end of 2000. Since Beer's Law is valid only for homogeneous canopies like those on the control plots, and the differences

between PAI values measured in 2000 and in 2002 on the control plots were small in comparison to the measurement error, measurements of PAR and PAR_0 taken in 2001 and PAI values from 2000 were used for the modelling of the annual cycle of PAI.

To consider the variation of the extinction coefficient k with different sky conditions, the radiation model RayMan (Matzarakis et al. 2000) was used to calculate the maximum possible incident radiation (cloudless conditions) G_{max} . In RayMan the optical transmissivity assumes the Linke turbidity approximation (VDI 1994). Limitations of the horizon (shading by the slopes), derived from fish-eye photographs, were taken into account to calculate times when direct sunlight was shaded by the horizon and the sites were hit by diffuse radiation only. Although RayMan gives global radiation G_{max} instead of PAR_{max} , G_{max} could be transformed into PAR_{max} by using simultaneous and continuous measurements of G and PAR above the control plots on the SW and NE slopes during the year 2001. The ratio of PAR to G turned out to be $1.94 \mu\text{mol m}^{-2} \text{s}^{-1}/(\text{W m}^{-2})$, and showed almost no variation between the two slopes or throughout the year (Mayer et al. 2002). PAR_{max} for the sites was calculated by the RayMan model on a 30-min basis throughout the year. To match calculated 30-min instantaneous values and measured 30-min averages, averages from two subsequent instantaneous values were used to achieve better agreement between modelled and measured values. For comparing measured PAR_0 and modelled PAR_{max} , overcast ($\text{PAR}_0/\text{PAR}_{\text{max}} < 0.4$), cloudy ($0.4 < \text{PAR}_0/\text{PAR}_{\text{max}} < 0.8$) and cloudless situations ($\text{PAR}_0/\text{PAR}_{\text{max}} > 0.8$) were defined; the limits were set empirically.

Using measurements of PAI determined for three different phenological stages, PAR_0 and PAR below the canopy, Beer's Law was solved for the extinction coefficient k on the basis of 30-min values separately for overcast, cloudy and cloudless situations as defined above. The extinction coefficient k was assumed to be valid for intervals with constant PAI, with a mean k for overcast, cloudy and cloudless situations and for each of the three phenological stages. The calculation of k defining a constant PAI value for the leafless period (NE slope: 1.1; SW slope: 0.7) and for the fully leafed period (NE slope: 5.2; SW slope: 5.1) used PAR data measured between 14 February 2001 and 16 April 2001 [days-of-the-year (doy) 45–106] for the leafless period, and from data measured between 13 September 2001 and 2 October 2001 (doy 256–275) for the fully leafed period. Since the foliage develops quickly when leaves unfold, and hence PAI changes quickly as well, the use of a constant PAI value for the period around leaf unfolding to calculate k is critical. According to the phenological observations, this period could be limited to the week from 5 May 2001 to 12 May 2001 (doy 125–132), reducing the number of samples used to calculate a mean k .

The next step was to use these calculated mean values of k and measured PAR, PAR_0 and the ratio $\text{PAR}_0/\text{PAR}_{\text{max}}$ for the modelling of PAI, divided again into overcast, cloudy and cloudless sky conditions. According to the phenological observations on the sites, the mean k for the leafless period was used for modelling PAI from 1 January to 30 April (doy 1–120) and from 1 November to 31 December (doy 305–365). After bud break between 1 May and 14 May (doy 121–134) the mean k for the leaf-unfolding period, and from 15 May to 31 October (doy 135–304) the mean k for the fully leafed period were used for the calculations. The resulting PAI values were averaged to give the mean daily PAI and treated with a 15-day running mean to reduce day-to-day variations.

Results

Results of PAI measurements

PAI measurements were conducted on four occasions in the leafless period in winter/spring 2000 under different light conditions to obtain PAI values for the leafless period. The first measurements at the end of February 2000 were made under ideal overcast conditions, resulting

Table 2 Mean plant area index (PAI) and error δ (absolute and relative to PAI) for beech stands with different silvicultural treatments (control C; light, 1, and heavy, 2, shelterwood felling) and on slopes with different aspects (NE and SW slopes) measured with the LAI-2000 plant canopy analyser in the leafless period. *Run* refers to the number of runs per plot conducted that day. *day* day of the year

Date (day)	Plot	Run	Mean PAI	δ (abs.)	δ (rel., %)
24 Feb 2000 (55)	NE-C	3	1.10	0.16	14.5
	NE-1	3	0.77	0.16	21.7
	NE-2	3	0.41	0.06	15.0
7 Mar 2000 (67)	NE-C	1	0.94	0.09	9.5
	NE-1	1	0.62	0.09	14.4
	NE-2	1	0.39	0.04	11.5
	SW-C	3	0.67	0.12	18.2
	SW-1	3	0.47	0.06	17.9
	SW-2	3	0.35	0.03	9.2
14 Mar 2000 (74)	NE-C	3	1.01	0.15	15.3
	NE-1	3	0.98	0.22	22.2
	NE-2	2	0.82	0.12	14.3
	SW-C	3	0.77	0.15	18.7
	SW-1	3	0.84	0.10	8.5
	SW-2	3	0.53	0.12	17.3
23 Mar 2000 (83)	NE-C	2	1.2	0.08	7.1
	NE-1	2	0.83	0.13	15.0
	NE-2	2	0.49	0.04	8.7
	SW-C	2	0.78	0.19	25.0
	SW-1	2	0.55	0.08	15.6
	SW-2	2	0.38	0.06	17.0

in mean PAI values of 1.1, 0.8 and 0.4 for the control plot, light shelterwood felling and heavy shelterwood felling on the NE slope respectively (Table 2). The measurement error, δ , was calculated from PAI, the number of samples and standard error of PAI, describing 95% confidence that the sampled mean is within some error of the population mean (Licor 1992). The mean values of δ obtained were 0.16 (relative error 14.5%) for the control plot, 0.16 (21.7%) and 0.06 (15%) for the light and the heavy shelterwood felling respectively. The results for the single runs are shown in Fig. 2. Measurements on a clear day (7

March 2000, day 67) resulted in mean PAI values of 0.9 ($\delta = 0.09 \equiv 9.5\%$) for the control plot, 0.6 ($\delta = 0.09 \equiv 14.4\%$) and 0.4 ($\delta = 0.04 \equiv 11.5\%$) for the thinned plots on the NE slope and slightly lower values on the SW slope: 0.8 ($\delta = 0.12 \equiv 18.2\%$, control plot), 0.5 ($\delta = 0.06 \equiv 17.9\%$, light shelterwood felling) and 0.4 ($\delta = 0.03 \equiv 9.2\%$, heavy shelterwood felling) (Table 2). Values for single runs are presented in Fig. 2. Although measurements on clear days should be performed during sunrise and sunset (Licor 1992), this was not possible in this case because of the remoteness of the sites and the time required to make measurements on all six plots. To avoid influences of direct sunlight on the results we shaded the sensor head carefully. Leblanc and Chen (2001) reported underestimation of PAI for the LAI-2000 plant canopy analyser when taking measurements on clear days because direct sunlight is reflected from the leaves of the canopy, and they presented a correcting scheme based on the possibility of neglecting sensor rings for PAI computations. Since the clear-day measurements of PAI were conducted in the leafless phenoseason when no leaves are present and the outer sensor ring was neglected when computing PAI, the resulting PAI is almost equal to measurements on an overcast day (24 February 2000, day 55) while the error δ is smaller on the clear day. The following measurements of PAI were all conducted without direct sunlight. On a day with changing sky conditions (14 March 2000, day 74) PAI in the thinned plots seems to be overestimated and the error δ is almost doubled compared to measurements on a clear day (7 March 2000, day 67). For the control plot on the NE slope and for all plots on the SW slope the results of PAI in a given plot differ significantly between runs, showing the influence of changing light conditions (Fig. 2). Despite above-canopy and below-canopy readings being taken simultaneously, it seems that the spatial difference between above-canopy and below-canopy readings was too big to cope with passing, low-altitude cumulus clouds. On 23 March 2000 (day 83), high cirrus clouds were passing

Fig. 2 Plant area index (PAI) and measurement error δ , determined by repeated measurements with the LAI-2000 plant canopy analyser in the leafless period for beech stands with different silvicultural treatments on two opposing slopes of a valley. On 7 March 2000 measurements were conducted under clear sky conditions, on 14 March 2000 changing sky conditions resulted in higher errors δ and probably overestimation of PAI. In February and on 23 March sky conditions were overcast

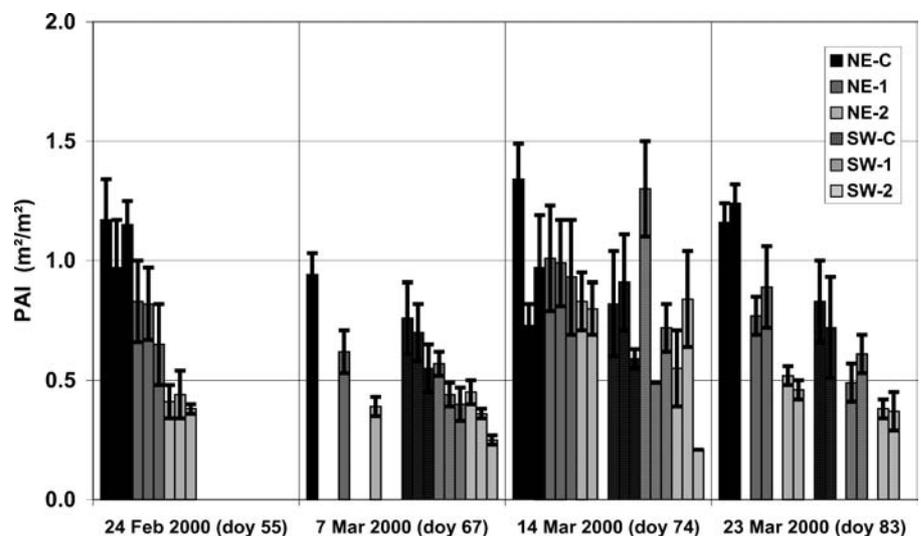


Table 3 Mean PAI and error δ (absolute and relative to PAI) for beech stands with different silvicultural treatments (control, C; light, I, and heavy, 2, shelterwood felling) and on slopes with different aspects (NE and SW slopes) measured with the LAI-2000 plant canopy analyser in the different phenoseasons (leafless, leaf unfolding, fully leafed) in the year 2000. Values are means calculated from all available measurements. *Run* refers to the number of runs per plot conducted in this phenoseason. *doy* day of the year

Phenoseason	Plot	Run	Mean PAI	δ (abs.)	δ (rel., %)
Leafless period	NE-C	9	1.06	0.13	12.5
	NE-1	9	0.83	0.16	19.6
	NE-2	8	0.53	0.07	12.8
	SW-C	8	0.74	0.15	20.1
	SW-1	8	0.63	0.08	14.7
	SW-2	8	0.43	0.07	14.2
Leaf unfolding period	NE-C	3	3.4	0.45	13.1
	NE-1	3	2.0	0.15	7.2
	NE-2	3	1.1	0.19	16.5
	SW-C	3	3.5	0.68	19.2
	SW-1	3	2.2	0.77	35.6
	SW-2	3	1.5	0.19	12.6
Fully developed canopy	NE-C	3	5.2	0.60	11.7
	NE-1	2	3.2	0.31	9.7
	NE-2	3	1.7	0.49	29.1
	SW-C	3	5.1	0.69	13.4
	SW-1	3	3.2	1.05	33.4
	SW-2	3	2.1	0.33	16.0

and shading the sun during the measurements, resulting in “stable” PAI calculations and small δ .

The mean PAI for all measurements in the leafless period was 1.1, 0.8 and 0.5 for the control plot, the light shelterwood plot and the heavy shelterwood plot, respectively, on the NE site. For the plots on the SW slope, the mean PAI in the leafless period turned out to be 0.7 for the control plot, 0.6 for the light felling and 0.4 for the heavy felling (Table 3). While in the NE plots the different silvicultural treatments were clearly reflected by PAI, on the SW slope differences between the control plot and light felling were quite small. But the basal area

differences between the control plot and light felling are also much smaller on the SW slope than on the NE slope (Table 1). So for the leafless period, different stand densities resulting from the silvicultural treatments could be reproduced by LAI-2000 measurements and the silvicultural treatments led to comparable results on the two slopes for the leafless period.

To gain an impression of the development of the canopy layer in the course of the phenological cycle, PAI measurements were conducted a few days after leaf unfolding began (5 May 2000, doy 126) and in September, when the canopy was fully leafed (21 September 2000 and 22 September 2000; doy 265 and 266). Since sky conditions were overcast, measurements on all plots should be representative. The results are presented in Fig. 3, where all runs, single PAI values and δ in comparison to the mean PAI of the leafless period are shown. As the canopy developed, the differences in PAI between the different silvicultural treatments increased, while the effect of similar silvicultural treatment on the two slopes stayed comparable. Reflecting the increased canopy heterogeneity, δ was bigger than in the leafless period, reaching more than 50% for some runs, especially for the light treatment on the SW slope. The mean value of PAI in the control plots was 3.4 on the NE and 3.5 on the SW slope in May, for the light shelterwood felling the mean PAI in May was 2.0 on the NE and 2.2 on the SW slope, and for the heavy shelterwood felling the values were 1.1 and 1.5 respectively. In September, the amount of foliage caused a mean PAI of 5.2, 3.2 and 1.7 in the control and in the silviculturally treated plots on the NE slope. On the SW slope, measurements showed a mean PAI of 5.1 in the control plot, 3.2 in the light shelterwood felling and 2.1 in the heavy shelterwood felling (Table 3). Once again, forest management led to comparable light conditions for plots that had undergone the same degree of thinning on both slopes.

In 2002 the measurements of PAI in all plots were repeated in July (9 July 2002; doy 190) when the foliage

Fig. 3 Plant area index (PAI) and measurement error δ , determined by repeated measurements with the LAI-2000 plant canopy analyser in the leafless period, shortly after leaf unfolding, and in the fully leafed period for beech stands with different silvicultural treatments on two opposing slopes of a valley. For the leafless period, values are given as a mean calculated from all available measurements taken in the leafless period

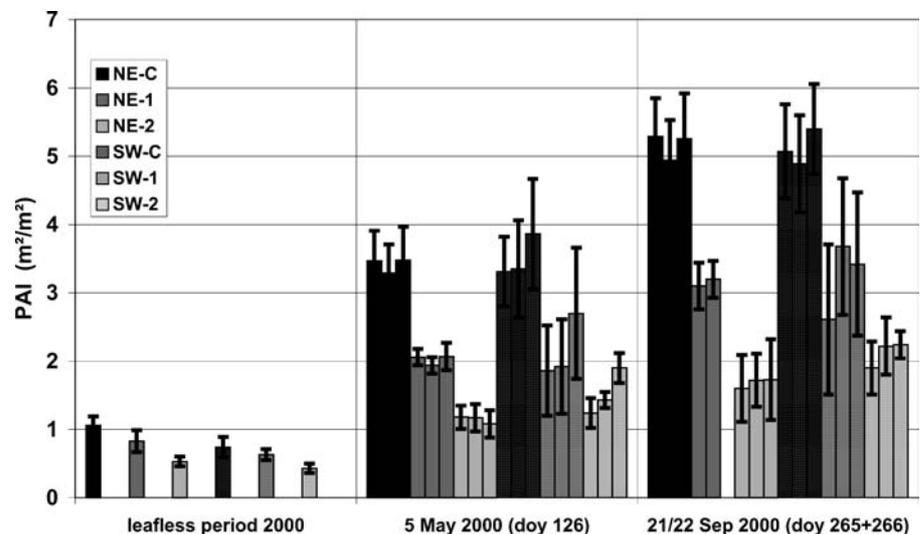


Fig. 4 Measured values of PAI on plots of different stand densities on a NE slope and a SW slope with fully leafed canopy in July 2002 (for the heavy shelterwood fellings: below and above the understory vegetation). For all plots, the measurements were conducted twice and the mean increase of PAI in comparison to the fully leafed canopy in 2000 is given (%)

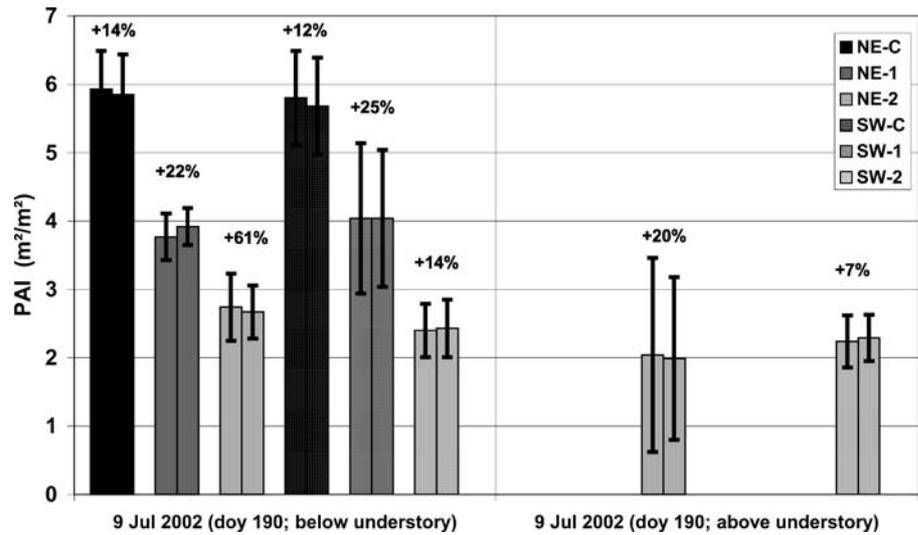


Table 4 Mean extinction coefficient, k , the standard deviation σ of k and the number of samples for two different beech stands with NE and SW aspect under different sky conditions in the leafless, the leaf-unfolding, and in the fully leafed canopy

Conditions	Slope	Leafless			Unfolding			Fully leafed		
		k	σ	Samples	k	σ	Samples	k	σ	Samples
Overcast	NE	0.991	0.220	689	0.620	0.071	106	0.751	0.042	167
Cloudy	NE	1.087	0.266	366	0.849	0.180	38	0.817	0.063	184
Cloudless	NE	1.172	0.481	485	0.914	0.267	94	0.833	0.163	122
Overcast	SW	1.249	0.285	684	0.521	0.043	101	0.681	0.030	189
Cloudy	SW	1.286	0.406	419	0.638	0.120	39	0.692	0.096	177
Cloudless	SW	1.392	0.607	457	0.785	0.286	96	0.755	0.154	107

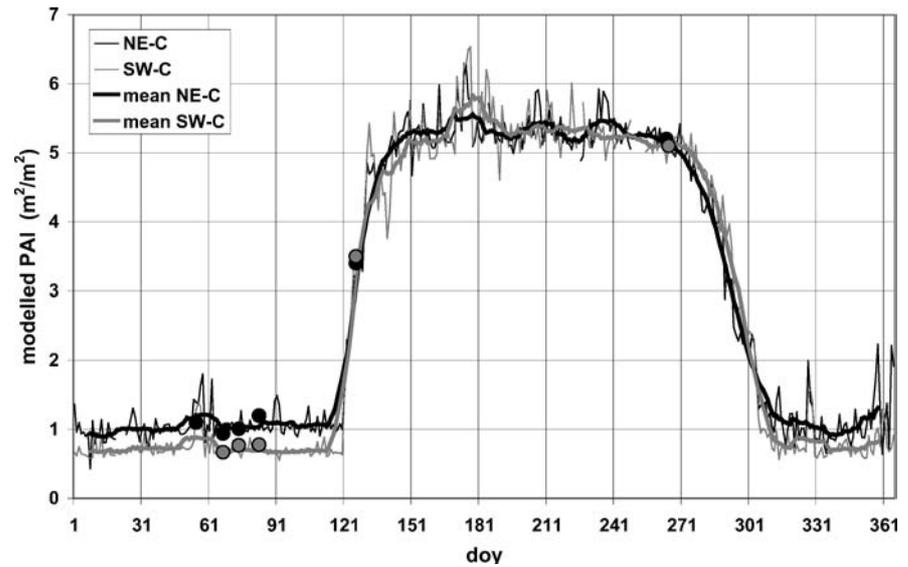
was fully developed. As light availability increased after the thinning in 1999, especially on the heavy shelterwood fellings, a pronounced development of understory vegetation was observed (esp. *Fraxinus excelsior* L., *Acer pseudoplatanus* L.), which reached a height of approximately 2.5 m in 2002. Results of the PAI calculations are presented in Fig. 4, comparing the years 2000 and 2002. For the control plots, the mean PAI rose from 5.2 to 5.9 (+14.1%) on the NE slope and from 5.1 to 5.7 (+12.1%) on the SW slope. This increase was of the same order as the measurement error. Where there had been light shelterwood felling, PAI increased by 22.2% (3.2 to 3.9; error < 10%) on the NE-slope and by 24.7% (3.2 to 4.0; error > 30%) on the SW slope, while the heavy shelterwood felling on the NE-slope led to an increase of 61.3% from 1.7 ($\delta = 0.49$) to 2.7 ($\delta = 1.30$). Taking readings above the understory vegetation resulted in a mean PAI of 2.0, meaning an increase of 20.2% compared to 2000. In the corresponding plot on the SW slope, the mean PAI was 2.4 ($\delta = 0.36$) below the understory and 2.3 ($\delta = 0.48$) above the understory; this is an increase of 14.2% below and of 7.1% above the understory.

Results of the modelling of the annual course of PAI

The extinction coefficient k for the control plots on the NE and SW slopes was calculated on the basis of PAI values and relative PAR irradiance, using Beer’s Law in the leafless period, at leaf-unfolding and during full-leaf-canopy conditions. The extinction coefficient was determined for overcast, cloudy and cloudless conditions. The resulting mean k , the number of samples used to calculate k and the standard deviation, σ , of k are presented in Table 4. The extinction coefficient of the canopies on both slopes was highest in the leafless period because there is a high interception of radiation by stems and twigs blocking forward scattering. Without leaves the canopy layer was relatively inhomogeneous with high σ values. When leaves were present in the growing season, radiation was not totally intercepted by the leaves but was partly transmitted through the closed canopy layer resulting in smaller k values and smaller σ . If cloudy and overcast conditions are compared to cloudless conditions, k and σ are higher in the latter case since scattering in the canopy layer has a larger impact on direct radiation than on diffuse radiation.

The annual cycle of the modelled PAI (Fig. 5) seems to be very reasonable, showing low values in the leafless period until bud breaking and a strong increase as leaves unfold. In summer, when the canopy was fully leafed, the

Fig. 5 Annual course of PAI for two beech stands with NE (black lines) and SW aspect (grey lines), modelled from measurements of photosynthetically active radiation above and below the canopy. PAI is given as daily mean (thin lines) and smoothed with a 15-day running mean (thick lines); the dots represent mean values of PAI measured by a LAI-2000 plant canopy analyser



modelled PAI remained relatively stable until autumn, when the leaves became senescent and PAI gradually decreased until they reached the levels of the leafless period again. Comparing modelled PAI values to measurements from 2000, the different values for the control plots on the NE and SW slopes were simulated very well for the leafless period. Snow on the sensors for PAR and PAR₀ around day 50 (mid February) and at the end of the year, especially on the colder NE slope, caused some variation in the calculated PAI. In summer, no reason for fluctuating PAI values can be given; on the basis of these day-to-day variations, the estimated modelling uncertainty may be about 0.5 (m²/m²), of the same order as the error of measurement presented in Figs. 2 and 3.

Discussion

Licor (1992) and Welles and Norman (1991) recommended that measurements should be taken only under homogeneous sky conditions, like stratus-type cloud cover or on clear days at dusk or dawn, so the sensor is not exposed to direct sunlight or scattered light from leaves. The measurements for the leafless period presented in this paper were conducted under differing sky conditions including overcast, clear (no direct sunlight on the sensors), changeable skies and under high cirrus clouds. However, only changeable cloud conditions seemed to have a notable influence on PAI measurements, probably because of the spatial difference between above-canopy and below-canopy readings. The PAI measurements conducted on a clear day in the leafless period resulted in PAI values close to those for an overcast day, since there was no reflection from leaves (Leblanc and Chen 2001) in the leafless period. In addition Leblanc and Chen (2001) presented a correcting scheme for the influence of sunlit leaves, based on the possibility of neglecting sensor rings for PAI computations.

Law et al. (2001) reported the use of an LAI-2000 plant canopy analyser in open-canopy ponderosa pine stands of different successional stages and management regimes, and Nackaerts et al. (2000) conducted measurements in small forest stands comparable in size to the stands near Tuttlingen-Möhringen on which this study is based. Chason et al. (1991) stated that the accuracy of LAI estimates from LAI-2000 measurements increases with the exclusion of outer rings, and they obtained their best results with rings 1 and 2 (out of 5) only. In this study the outer ring of the LAI-2000 sensor was excluded for the computation of PAI values since neighbouring plots with different stand characteristics and the slope would have influenced the measurements.

Dufrêne and Bréda (1995) compared PAI and LAI estimates from LAI-2000 measurements with litter measurements and observed that the LAI-2000 analyser underestimates LAI by 17% when only the three central rings are used, but by 30% when the four central rings are considered. Prskawetz and Lexer (2001) compared allometric determination of LAI and measurements by an LAI-2000 analyser for stands of young beech and found that the LAI-2000 underestimated the value by 32%; neglecting ring 5 gave better results for LAI. They concluded that estimation of LAI by means of an LAI-2000 analyser has to be used with caution. As the PAI measurements made for this study were repeated up to three times under the same conditions, samples being taken consecutively on the same day, the variability of the PAI estimates between different runs gives information about the accuracy of the PAI measurement. In general, the accuracy seems to be about 15%, while in some cases (thinned plots) it exceeded 30% (Tables 2 and 3). Chason et al. (1991) compared LAI estimates from litter collections to those from LAI-2000 measurements in a mixed-age oak/hickory forest and also found the plant-canopy analyser to underestimate LAI. However, they stated that the plant canopy analyser was well suited to detecting LAI

differences between different stands, to measure seasonal/temporal changes of LAI or to obtain vertical profiles.

As in this study one of the main goals was to verify whether the different silvicultural treatments led to (a) comparable conditions in plots with the same kind of silvicultural treatment and (b) clearly different conditions in plots with different stand densities, it was more important to obtain reliable relative differences than absolute values of PAI.

The application of Beer's Law to forest canopies is quite common (Kull et al. 1999; Johansson 1996; Dufrène and Bréda 1995; Yang et al. 1993; Baldocchi et al. 1984a), but since the extinction coefficient k is not constant and depends on certain stand characteristics, the wavelength of the incoming radiation (PAR or global radiation) or the index used (PAI or LAI), the comparison of k with results from other authors is hardly possible. In this study k for the PAR waveband and for PAI was found to be between 1.392 and 0.991 for the leafless period, between 0.914 and 0.521 for leaf-unfolding and between 0.833 and 0.681 for the fully leafed period (Table 4). For some birch stands of differing density in Sweden, Johansson (1996) reported k values in the range of 0.63 and 3.09 for the PAR waveband and LAI. Baldocchi et al. (1984a) reported k values (based on PAR) in the range of 0.655 (for PAI) and 0.732 (LAI) for an oak/hickory forest in September. Yang et al. (1993) determined k (PAR waveband, referring to PAI) to be 0.79 for a defoliated/refoliated mixed oak stand. For an oak stand in the United Kingdom, Kull et al. (1999) calculated $k = 0.82$ (PAR waveband and LAI). Dufrène and Bréda (1995) used Beer's Law in sessile oak (*Quercus petraea*) stands in France and obtained extinction coefficients k of 0.38 and 0.29 for solar radiation and PAI.

The PAI is important in studies of forest/atmosphere interaction, not only for studies on the radiation environment within canopies but also for the water use of a stand (Keitel et al. 2003; Federer 1995) as transpiration rates depend on the leaf area. In studies of forest ecosystems the PAI is used for the calculation of fluxes of energy and CO₂ (Schmid et al. 2000), which have been the focus of research in recent years because of the role of CO₂ in global climate change.

There exist only few studies on the annual cycle of PAI in forests. Although the LAI-2000 analyser is a non-destructive and fast instrument for obtaining reliable PAI values compared to taking litter or vegetation samples, its use is limited to certain sky conditions and it is hardly possible to make measurements regularly (weekly) throughout the whole phenoseason or to take measurements when PAI is changing fast in the leaf-unfolding period and during leaf fall (Schmid et al. 2000). Leblanc and Chen (2001) published PAI values for a deciduous forest taken on more than ten occasions throughout the growing season and Chason et al. (1991) made measurements during late summer and during leaf fall in an oak/hickory forest. In this study, the annual cycle of PAI was calculated from continuous radiation measurements and only a few PAI measurements for the whole year

including the leaf-unfolding period and during leaf fall. It would be interesting to see whether the simple application of Beer's Law presented in this study is able to reflect canopy growth/canopy closure for a couple of subsequent seasons when the extinction coefficients found in this study are used.

Conclusions

In this study measurements of the plant area index (PAI) were conducted using a LAI-2000 plant canopy analyser in several beech stands of different stand density in south-west Germany. The measurements were done in the leafless period, during leaf unfolding and with fully developed canopies; the measurement error was about 15% though in some cases it exceeded 30%. Results showed that the different silvicultural treatments led to (a) comparable conditions in plots with the same kind of silvicultural treatment and (b) clearly different conditions in plots with different stand densities.

PAI values in combination with photosynthetic active radiation (PAR) measured above and below the closed canopy were used to calculate the extinction coefficient k , using Beer's Law. In this study, k for the PAR waveband and for PAI was found to be between 1.392 and 0.991 for the leafless period, between 0.914 and 0.521 for leaf/unfolding and between 0.833 and 0.681 for the fully leafed period; these values are comparable to results obtained in similar studies. Using continuously measured PAR, Beer's Law was used to calculate PAI values for periods when no PAI measurements were available. As a result, data on PAI were available for the whole year, including leaf unfolding and during leaf fall, and can be used in forest ecosystem studies (water use and evapotranspiration).

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