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Long-term variations in leaf area index and light extinction in a *Fagus sylvatica* stand as estimated from global radiation profiles

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With 6 Figures

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Summary

The paper presents a model that estimates leaf area index (LAI) from above- and below-canopy global radiation measurements. The approach is based on a detailed description of radiation regime above and below the canopy. One EuroFlux site, a beech forest (*Fagus sylvatica* L.) at Hesse, France was selected for model testing. The time-courses of daily LAI from 1996 to 2001 were simulated by the model. Since the simulated LAI curves include some random daily variations due to the quality of global radiation measurements, these were further smoothed by Fast Fourier transform and convolution using a 5-day window. The direct model output and the smoothed data by Fast Fourier transform and convolution using a 5-day window all agreed well with the *in situ* measurements. The r^2 of daily modeled LAI, Fourier transformed and convolution smoothed LAI with respect to measured LAI were 0.85, 0.89 and 0.84, and the corresponding RMSE were 0.56, 0.62 and 0.42 respectively. Relative evident noise was noted during the “leaf constant” period in each year. The analysis of normalized deviation during this period in response to environmental parameters revealed that no statistical relationship could be found for daily average temperature, VPD, wind velocity and fraction of diffuse radiation. However, in 65% of cases with positive normalized deviation during the “leaf constant” period precipitation occurred, indicating an effect of precipitation on model output. The daily and seasonal variation of the estimated extinction coefficient k was examined, since treating k as a constant may lead to large changes in the estimates of LAI via direct

application of the Lambert-Beer law. Finally, the paper has also compared MODIS LAI predictions for the tower site during the year 2001 with the convolve smoothed model output. While a similar pattern is found during mid-summer, MODIS underestimated LAI during the “leaf constant” period. Larger as yet unexplained deviations are found during winter and spring before the “leaf constant” period. Since the model is not very sensitive to weather conditions, it can be used to provide daily LAI from the daily global radiation measurements and offers an opportunity to include phenological information into gas exchange models which require LAI as input.

1. Introduction

Leaf area index (LAI), defined as the projected area of leaves per unit of ground area (Ross, 1981), is a key functional determinant of energy, water vapor, and carbon dioxide exchange between terrestrial ecosystems and the atmosphere (Bonan, 1993). Seasonal LAI changes in deciduous forests are obvious and dramatic, dominated by springtime leaf expansion and autumn senescence. Even in coniferous forest stands, seasonal variations in LAI during growth cycles of 25 to 30% may occur (Chen, 1996). A new understanding of this variation and its

influence on annual ecosystem water and carbon balances is needed (Falge et al., 2002), but data on temporal LAI variation in forest ecosystems remain rare (Murphy and Lugo, 1986; Maass et al., 1995).

Estimates of LAI may be obtained by harvesting (Gower et al., 1992), application of allometric equations to observations of individual plant size, e.g. diameters of trees (Gower et al., 1999), and by collecting leaf litterfall (Gower et al., 1999). However, such direct measures are labor intensive and seldom permit characterization of the temporal dynamics of leaf area development (Chason et al., 1991). Thus, indirect methods based on light transmission through plant canopies have been developed and numerous instruments to estimate LAI have become commercially available (cf. Decagon ceptometer, LiCor LAI-2000, DEMON and TRAC; Fassnacht et al., 1994; Chen et al., 1997; Welles and Norman, 1991). Even so, only few published studies have reported on temporal dynamics of LAI as observed with these methods.

In one such study, Maass et al. (1995) utilized canopy light transmission and the Beer-Lambert equation to quantify monthly LAI changes in a tropical deciduous forest ecosystem on the west coast of Mexico. The extinction coefficient k was established by regression analysis of photosynthetically active radiation (PAR) as a function of cumulative LAI as determined at one point in time during October 1991 when the canopy was fully developed. This k value was then used to invert the Beer-Lambert equation and to estimate LAI at different times.

The Beer-Lambert law assumes that leaf inclination angles are spherically and randomly distributed and that the foliage is distributed randomly in space (Jarvis and Leverenz, 1983). These assumptions imply that LAI normal to a beam of radiation is independent of the angle at which the radiation strikes the canopy (Landsberg, 1986). In most real canopies, the leaf angle distribution is more generally described by prolate or oblate spheroids, rather than spheres. By adjusting the ratio of horizontal to vertical axis of the spheroid, leaf angle distributions of any canopy from erectophile to planophile can be simulated (Campbell, 1986). Based on the ellipsoidal model, Campbell (1986) described the

relationship between extinction coefficient k , the solar zenith angle and canopy structure. A further factor affecting the radiation exchange of forest canopies is the clumping of leaves. The clumping index was proposed by many researchers to account for non-random distribution of foliage in gap fraction analysis (e.g. Nilson, 1971; Chen, 1996) and in derivation of appropriate values for LAI. Kucharik et al. (1998a) indicated that the clumping index was dependent on zenith angle in the canopy.

Thus, the approach of Maass et al. (1995) can be viewed as a first approximation approach which in certain field studies may provide important insight on ecosystem function. Nevertheless, a better understanding of the role of inter-annual variability in LAI in terms of carbon sequestering and best utilization of information from sites characterized by frequent direct determinations of LAI as well as long-term observations of ecosystem carbon and water exchange will be obtained, if improved theory is applied, as for example in the interpretation of continuous measures of canopy light interception. This paper utilizes a model that extends the Beer-Lambert law to interpret changes in light interception in a deciduous beech (*Fagus sylvatica*) forest site in Hesse, France where frequent direct determinations of LAI by various methods have been undertaken over a period of seven years. We take into account the effect of zenith angle and clumping index to describe the continuous, time-dependent change in both the extinction coefficient and in LAI from measured above- and below-canopy global radiation. We compare model output with the direct measurements made on the ground at the Hesse site and with remote observations of the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Earth Observing System (EOS) Terra platform. Potential causes for the remaining differences between the improved model and the various sets of observations are discussed.

2. Methodology

2.1 Site and field measurements

The research area is one of the tower sites of the Euroflux network (Baldocchi et al., 1996)

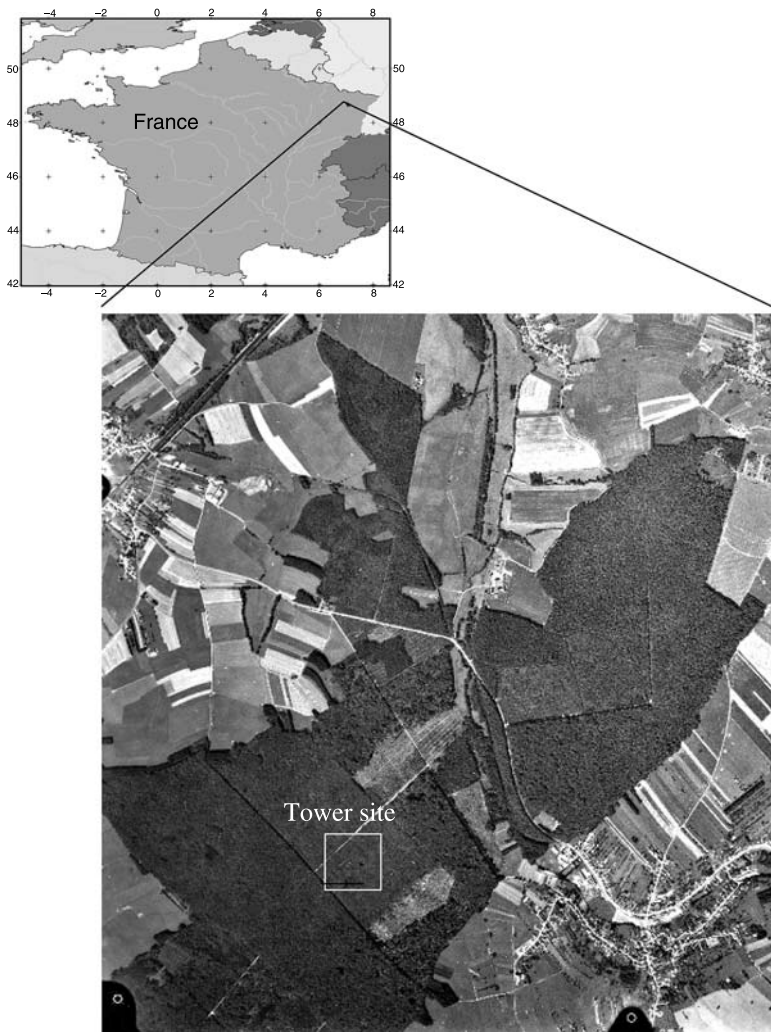


Fig. 1. Location of Hesse forest site, France

in Hesse, France (48°40'N, 7°05'E, cf. Fig. 1). The tower for flux observations was constructed within a 0.6 ha experimental plot with naturally established beech forest at the center of a 65 ha homogeneous forest area. The dominant species is beech (*Fagus sylvatica* L.) with a cover of more than 90 percent. Other tree species include *Carpinus betulus* L., *Betula pendula* (Roth), *Quercus petraea* (Matt.), and *Larix decidua* (Mill.). The understory vegetation is sparse due to dense canopy closure. The stand age was on average 30 years in 1996 with a stand density of 3800 stems ha⁻¹, and basal area 19.6 m² ha⁻¹. Aboveground biomass is ca. 99 tons ha⁻¹. Average tree height and circumference (at 1.3 m) were 12.7 m and 22.7 cm, respectively in 1996 (Granier et al., 2000).

A global radiometer (Cimel, France) and other climate monitoring instruments were installed at the height of 17.5 m. Within and below the canopy, global radiation was measured at 1, 8, 10, 12 m height using 33 cm long linear pyranometers (INRA, France). The daily summed values of global radiation above the canopy and at 1 m height were used to estimate seasonal changes in light extinction and LAI. Examination of potential time-dependent hourly changes in light extinction is based on a theoretical redistribution of daily radiation input (Eqs. (2) through (9)) rather than on short-term observations, since these considerations are not included in direct comparisons with observed data.

Both direct and indirect methods have been used to estimate LAI at Hesse (Granier et al.,

Table 1. Direct and indirect observations of LAI in Hesse Forest via litter collection and transect studies with the DEMON instrumentation

Method	Year	Date	LAI	Maximum LAI during the year
DEMON	1996	July	6.1(0.2)	6.1(0.2)
Litter Collection	1996	01/10/96	4.93	5.7*
Litter Collection	1996	10/10/96	4.48	
Litter Collection	1996	16/10/96	3.69	
Litter Collection	1996	24/10/96	2.26	
DEMON	1997	July	6.5(0.5)	6.5(0.5)
Litter Collection	1997	18/09/97	5.52	5.6*
Litter Collection	1997	01/10/97	5.48	
Litter Collection	1997	08/10/97	5.03	
Litter Collection	1997	15/10/97	4.30	
Litter Collection	1997	24/10/97	3.74	
Litter Collection	1997	30/10/97	3.20	
Litter Collection	1997	14/11/97	1.75	
Litter Collection	1997	24/11/97	1.06	
Litter Collection	1997	09/12/97	0.69	
Litter Collection	1998	06/10/98	6.94	7.36
Litter Collection	1999	27/10/99	0.85	4.97
Litter Collection	2000	10/10/00	6.97	7.33
Litter Collection	2000	26/10/00	5.21	
Litter Collection	2000	02/11/00	2.21	
Litter Collection	2000	17/11/00	0.32	
Litter Collection	2001	23/10/01	6.00	7.37
Litter Collection	2001	06/11/01	4.42	

* Maximum according to litter collection

2000). Litter was collected during autumn using forty-two 0.25 m² litter traps. Dry mass of litter was measured weekly during the leaf-fall pe-

riod, while a sub-sample of leaves was taken every two weeks to determine specific leaf area. A DEMON leaf area meter (CSIRO, Australia) was used in 1996 and 1997 to periodically measure gap fractions on bright days when leaf expansion was maximum (seven transects approximately 25 m long through the plot). The measured LAI values by litter collection and DEMON are given in Table 1 (standard deviation DEMON indicated in brackets). The LAI determined by using DEMON is larger than that by litter collection, which may occur

because the DEMON leaf area meter includes the visible fraction of the woody material of the trees (Granier et al., 2000). The maximum LAI values for each year estimated by litter fall collection are also shown in Table 1. LAI was further obtained for 2001 as standard level 3 output (MOD15, collection 004) of the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Earth Observing System (EOS) Terra platform from the EROS data center (Data Active Archive Center – EDC DAAC) at 1 km resolution. The progress made with MODIS in standardizing outputs is extremely important for ecological studies and these data provide an important perspective in the analysis of LAI temporal dynamics.

2.2 Incoming radiation above the canopy

2.2.1 Separation of direct and diffuse radiation

Several algorithms have been proposed to separate direct and diffuse radiation depending on atmospheric transmittance at different time scales, e.g. hourly, daily or monthly (Liu and Jordan, 1960; Ruth and Chant, 1978; Orgill and Hollands, 1977; Bruno, 1978; Erbs et al., 1982). Spitters et al. (1986) recommended the following algorithm for daily global radiation flux:

$$f = \begin{cases} 1 & S_{c,d}/S_{0,d} < 0.07 \\ 1 - 2.3(S_{c,d}/S_{0,d} - 0.07)^2 & 0.07 \leq S_{c,d}/S_{0,d} < 0.35 \\ 1.33 - 1.46 S_{c,d}/S_{0,d} & 0.35 \leq S_{c,d}/S_{0,d} < 0.75 \\ 0.23 & S_{c,d}/S_{0,d} \geq 0.75 \end{cases} \quad (1)$$

riod, while a sub-sample of leaves was taken every two weeks to determine specific leaf area. A DEMON leaf area meter (CSIRO, Australia) was used in 1996 and 1997 to periodically measure gap fractions on bright days when leaf expansion was maximum (seven transects approximately 25 m long through the plot). The measured LAI values by litter collection and DEMON are given in Table 1 (standard deviation DEMON indicated in brackets). The LAI determined by using DEMON is larger than that by litter collection, which may occur

where f is the fraction of diffuse radiation in the daily total radiation received at the ground (here over the canopy, $S_{c,d}$), and $S_{0,d}$ denotes the daily extra-terrestrial radiation. Further details are given in the Appendix.

2.2.2 Diurnal courses of global diffuse and direct radiation above the canopy

The diurnal course of global radiation is assumed to follow a cosine function with the maximum value at local solar noon. Properties of the atmosphere are

considered here as constant over the course of a day. According to Spitters et al. (1986), the instantaneous transmittance is estimated as:

$$\tau = a + b \cos \theta \quad (2)$$

where θ is the sun zenith angle, and a and b are empirical regression coefficients. Instantaneous global radiation can then be calculated as:

$$S_g = \frac{\cos \theta (1 + c * \cos \theta) S_{c,d}}{\int_D \cos \theta (1 + c * \cos \theta) dt} \quad (3)$$

where $c = b/a$; D denotes the domain of day length in hours (see Appendix A for calculation).

The instantaneous diffuse radiation can be approximated as

$$S_{\text{dif}} = S_{\text{dif},d} \cdot \frac{S_0}{S_{0,d}} \quad (4)$$

where S_0 is the potential solar radiation (see Appendix A for calculation).

The circumsolar radiation has to be subtracted from the diffuse flux and added to the direct flux due to the predominantly forward-directed Mie scattering of aerosols. Thus the algorithm to calculate the instantaneous fraction of diffuse radiation needs to be adjusted (Spitters, 1986):

$$f' = \frac{f}{1 + (1 - f^2) \cos^2 \theta \sin^3 \theta} \quad (5)$$

By replacing $S_{\text{dif},d} = f' S_{c,d}$, the instantaneous diffuse radiation is calculated as

$$S_{\text{dif}} = S_0 f' \cdot \frac{S_{c,d}}{S_{0,d}} \quad (6)$$

Thus, the instantaneous direct solar radiation can be obtained as

$$S_{\text{dir}} = S_g - S_{\text{dif}} \quad (7)$$

2.3 Radiation interception

At the solar zenith angle θ , transmittance of direct radiation through the canopy, $T_{\text{dir}}(\theta)$, depends on canopy structure, foliage amount, and leaf optical properties (Nouvellon et al., 2000). In the case of a homogeneous and infinite canopy, with randomly dispersed, black leaves (leaf transmittance $\tau_l = 0$), the transmittance $T_{\text{dir}}(\theta)$ can be expressed as (Anderson, 1966):

$$T_{\text{dir}}(\theta) = \exp \left[\frac{-G(\theta)}{\cos \theta} \text{PAI} \right] \quad (8)$$

where PAI is the plant area index, the ratio $G(\theta)/\cos \theta$ is the directional extinction coefficient ($k(\theta)$) of direct radiation in the canopy, and $G(\theta)$ is the fraction of foliage projected in the direction θ , given by

$$G(\theta_s) = \int_0^{\pi/2} A(\theta_s, \theta_l) g(\theta_l) d\theta_l \quad (9)$$

where $g(\theta_l)$ is the leaf inclination angle distribution (Campbell, 1986, 1990), and $A(\theta_s, \theta_l)$ the projection of unit leaf area with an inclination angle θ_l . $A(\theta_s, \theta_l)$ is given by Warren Wilson (1960) as

$$\begin{aligned} A(\theta_s, \theta_l) &= \cos \theta_s \cos \theta_l & \theta_s + \theta_l \leq \frac{\pi}{2} \\ A(\theta_s, \theta_l) &= \cos \theta_s \cos \theta_l \\ &\quad \times \left| \frac{2(\phi_0 - \tan \phi_0)}{\pi} - 1 \right| & \theta_s + \theta_l > \frac{\pi}{2} \end{aligned} \quad (10)$$

with

$$\phi_0 = a \cos(-\cot \theta_s / \tan \theta_l) \quad (11)$$

Since leaves cannot be treated as opaque elements in the domain of the solar spectrum, the extinction coefficient $k(\theta)$ should be modified by $(1 - \tau_l)$, where τ_l is the mean leaf transmittance (Monteith, 1969; Nouvellon et al., 2000)

$$T_{\text{dir}}(\theta) = \exp[-k(\theta)(1 - \tau_l)\text{PAI}] \quad (12)$$

PAI is an index including all the elements such as leaf, branch, and stem that contribute to the projection area with respect to the ground. Obviously the branch and stem have different optical characteristics from those of leaves and are suitable to be treated as opaque elements. Therefore Eq. (8) (or (12)) can be modified as:

$$T_{\text{dir}}(\theta) = \exp[-k(\theta)(1 - \tau_l)\text{LAI} - k_w(\theta)\text{WAI}] \quad (13)$$

where WAI is woody area index including both branch and stem, and $k_w(\theta)$ is the extinction coefficient of woody elements. By assuming randomly dispersed branches and stems within the canopy, $k_w(\theta)$ can further be simplified to discard θ . Both $k_w(\theta)$ and WAI can be obtained from measurements before leaf flushing when LAI = 0.

For diffuse radiation, the transmittance can be estimated following Welles and Norman (1991):

$$T_{\text{dif}} = \frac{\int_0^{\pi/2} \Gamma(\theta) T_{\text{dir}}(\theta) \sin \theta \cos \theta d\theta}{\int_0^{\pi/2} \Gamma(\theta) \sin \theta \cos \theta d\theta} \quad (14)$$

where $\Gamma(\theta)$ is the intensity distribution of diffuse radiation above the canopy. The transmittance of diffuse radiation remains constant over the day.

2.3.1 Extinction coefficient k

The extinction coefficient represents the area of shadow cast on a horizontal surface by the canopy divided by the area of leaves in the canopy (Monteith, 1975) or the average projection of leaves on to a horizontal surface. It can be estimated from a theoretical consideration of the orientation of foliage elements (Ross, 1981). Direct estimation of k using these methods requires detailed measurements of leaf angle distribution (LAD) within the canopy (Norman and Campbell, 1989). It is often calculated by noting that the distribution of leaf area in a real canopy may be approximated by the distribution of surface on spheres, cylinders and cones (Monteith, 1975; Campbell, 1977). Values for k , therefore, can be calculated by finding the ratio of shadow area to surface area for these shapes. These models provide simple formulae for calculation, but their density functions for foliage inclination angle are generally only very crude approximations to actual foliage inclination angle densities. Only the spherical distribution provides a range of leaf angles. For all others, one assumes that all of the leaves in the canopy are oriented at a single angle, whereas leaf angle distributions (LAD) are continuous. Campbell (1986) suggested a more general approach by deriving a generalized equation using an ellipsoidal inclination angle distribution.

The extinction coefficient can be defined as (Norman and Campbell, 1989):

$$k(\theta) = \frac{\sqrt{x^2 + \tan^2 \theta}}{x + 1.774(x + 1.182)^{-0.733}} \quad (15)$$

where $x = b_1/a_1$; b_1 is the horizontal semiaxis length and a_1 is the vertical semiaxis length (Campbell, 1986).

2.3.2 Modification of k due to clumping of leaves

The Poisson model used to derive Eq. (12) assumes that the foliage elements are randomly dispersed. This assumption does not hold for canopies with regular leaf dispersion, where the model is known to overestimate the gap fraction,

and for canopies with clumped dispersion, where gap fraction is underestimated (e.g. Nilson, 1971; Ross, 1981; Baldocchi et al., 1985; van Gardingen et al., 1999). The underestimation can be serious in highly clumped canopies. Nilson (1971) proposed a statistical model based on the theory of Markov processes in which the extinction coefficient is modified by a parameter Ω [so-called 'Markov parameter' (Kuusk, 1995; Andrieu et al., 1997), 'clumping index' (Chen and Black, 1991), or 'leaf dispersion parameter' (Baret et al., 1993; Nouvellen et al., 2000)]. Values of $\Omega(\theta)$ are greater than 1.0 for regular foliage dispersions, equal to 1.0 for a random distribution, and less than 1.0 for clumped canopies (Nilson, 1971). Multiplying the extinction coefficient by the parameter Ω will lead to a reduction in extinction in clumped canopies and an increase in regular canopies.

Using values of crown diameter, tree density, crown porosity, and crown depth, Kucharik et al. (1998a) derived via Monte Carlo simulation a relationship between canopy clumping factors and zenith angle. The simple empirical approach to estimating clumping factors avoids laborious measurements of canopy gap-size distribution as a function of angle, which can only be made with specialized instrumentation. They suggested the values of Ω_{\max} for any forest stand may be obtained as:

$$\Omega_{\max} = \min\left(1.0, \left(\frac{ND_1}{\sqrt{A}}\right)^{0.7}\right) \quad (16)$$

where N is the number of stems within ground area A , and D_1 is crown diameter. The relationship between $\Omega(\theta)$ and Ω_{\max} can be represented as:

$$\Omega(\theta) = \frac{\Omega_{\max}}{1 + c_1 \exp(-2.2 \times \theta^p)} \quad (17)$$

where c_1 is a canopy specific coefficient, Ω is in radian, p is a function of x , given as:

$$p = \begin{cases} 1.0, & \text{if } x \leq 0.164 \\ -0.461/x + 3.8, & \text{if } 0.164 < x < 1.0 \\ 3.34, & \text{if } x \geq 1.0 \end{cases} \quad (18)$$

when $x \geq 1.0$, it is the case for crowns with spherical shape which may be applied to many full-cover deciduous canopies, while $x \leq 0.164$ for typical tall, thin coniferous trees.

2.4 Below canopy radiation

Finally the radiation that can be received below the canopy is estimated as:

$$S_{g,d} = \int_0^{\omega_s * \frac{24}{\pi}} [T_{\text{dir}}(\theta)(S_g - S_{\text{dif}}) + T_{\text{dif}}S_{\text{dif}}] dt \quad (19)$$

where $S_{g,d}$ is the daily below canopy global radiation, ω_s is sunrise time angle (see Appendix).

2.5 Estimation of PAI, WAI and LAI

Plant area index, PAI (Eq. (12)), can be solved by inverting Eq. (19) for each pair of above and below canopy daily radiation measurements. Implicit in this inversion is an estimation of the parameters x and c_1 in Eqs. (17) and (18), and, thereby, determination of the extinction coefficient k and clumping index Ω . LAI can then be estimated by subtracting WAI determined in springtime before leaf flushing (Eq. (13)) from PAI. Here the effect of woody elements (stem and branch) has been assumed as a constant through the year. Some debate has focused on whether the contribution of branches and stems should be subtracted from indirect determinations of LAI (Deblonde et al., 1994; Chen et al., 1997). Kucharik et al. (1998b) analysed LAI with different methods in a boreal area and found that the contribution of branches to the indirect LAI estimate was less than 10%, while stem contributions were large. When branches are masked by leaves, then this part will not directly contribute to error in the LAI estimates. This is true for most indirect methods that use the blue domain of the spectrum where leaves may be treated as opaque elements. But for global radiation, whether covered or not, woody elements always play an important role in radiation interception. Thus, branches continue to contribute to the indirect LAI estimate, suggesting that the value reported by Kucharik et al. (1998b) is probably too low. Moreover, the effect of stems, a large proportion of the woody materials influencing radiation interception and response of a below-canopy sensor, should be constant over the seasonal course. Thus, we have assumed that the effect of woody elements is constant and should be subtracted from PAI to obtain LAI.

3. Results and discussion

3.1 Canopy structure parameters

The two canopy structural parameters, x and c_1 , are needed to determine the extinction coefficient k and clumping index Ω . The parameter x defines the ratio of the horizontal semiaxis length to that of the vertical semiaxis length (Campbell, 1986; required in Eq. (15) and Eq. (18)). For the Hesse tower site, the average crown projection is 2.7 m² and canopy depth is ca. 6 m. Therefore, calculated x is approximately 0.309.

The parameter c_1 is obtained by inverting Eq. (17) for a known value of the clumping index (Kucharik et al., 1998a). Since $ND_1/(A^{1/2}) > 1.0$, $\Omega_{\text{max}} = 1.0$. We assumed that $\Omega(0)$ is equal to 0.9 at the zenith angle $\theta = 0$ for the Hesse tower site, a value typical for fully developed broad-leaf canopies (Kucharik et al., 1999). Inserting these values ($\theta = 0$, $\Omega(0) = 0.9$, $\Omega_{\text{max}} = 1.0$) into Eq. (17) and solving for c_1 yields 0.11.

WAI is required to finally estimate LAI from the calculated PAI. WAI was determined by averaging the PAI before Julian day 100 (April 10th) when there were no leaves on the trees. The average value of WAI for Hesse forest site was 1.1 before thinning in 1999, which decreased WAI to 1.0. The WAI value recovered to 1.1 in 2000 and showed an increasing trend in 2001 and 2002 (1.2 and 1.4 respectively). Thus, the measured LAI using DEMON in year 1996 and 1997 can be further corrected by limiting the effect of stem and branch to obtain values of 5.0 and 5.4 respectively, both of which are slightly lower than determined via litter collection (Table 1).

3.2 Comparison of measured and modelled LAI

Direct and indirect measurements of LAI (Table 2) are compared to continuous model output in Fig. 2. Three developmental stages may be distinguished which are discussed separately:

- a) Leaf senescent period (ca. Julian day 280 to the end of the year): LAI decreases during this period from the maximum to zero at a relatively slow rate compared with the leaf production period. During this phase, the greatest number of ground-based measurements of LAI are available based on litter fall. Thus,

Table 2. Statistical results of the performance of model for LAI estimation from global radiation interception (direct model output from observations on each day, Fast Fourier transformation of data and convolve smoothed data) in comparison with LAI from litter collection at Hesse Forest site

LAI estimation	r^2	RMSE
Direct model output	0.93	0.56
Fast Fourier transformed	0.95	0.62
Running mean smoothed	0.97	0.42

success of the model during this period is critical with respect to its calibration for the site. The comparison is favorable and is discussed further below (cf. Fig. 3). From the data in

Table 2 (less obvious in Fig. 2), it is apparent that the rate of senescence varies from year to year in response to environmental factors. Thus, this phase of slow change in system behavior also provides an extremely important period for comparison of ground-based determinations and remotely sensed vegetation indices.

- b) Leaf constant period (ca. Julian day 141 to 280): A direct comparison during this period is possible between the results obtained with DEMON and with light extinction. LAI is hypothesized to remain constant after leaf expansion and before senescence begins in late summer. However, based on apparent

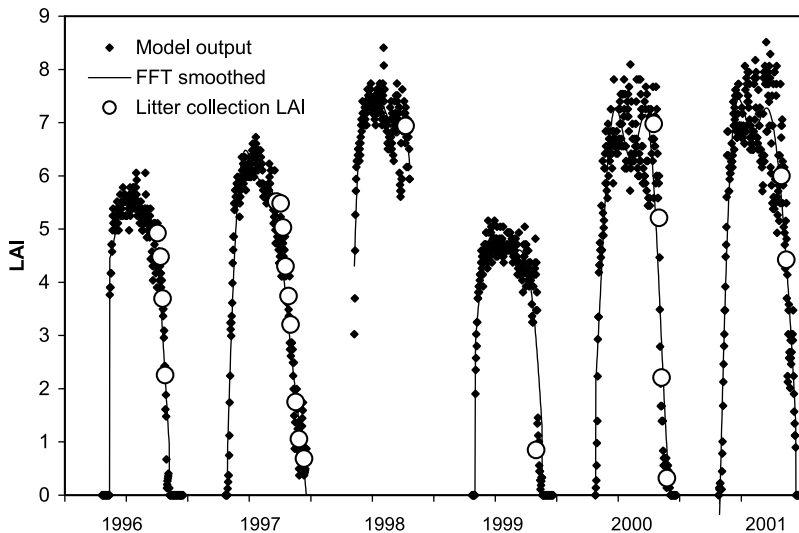


Fig. 2. Estimated LAI (direct model output, Fast Fourier transformed (FFT) and convolve smoothed) and litter collection data in Hesse Forest, France from 1996 to 2001

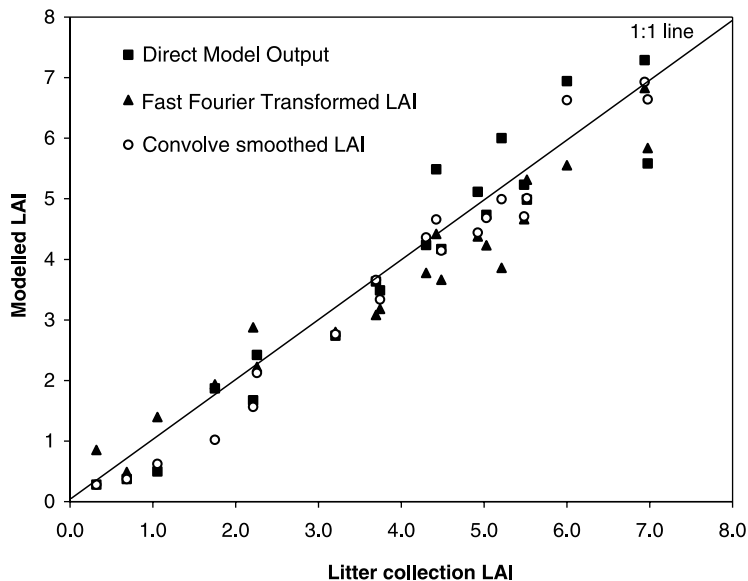


Fig. 3. Scatter diagrams between estimated LAI (direct model output, Fast Fourier transformed and convolve smoothed) and litter collection data in Hesse Forest, France

Table 3. Statistics of estimated LAI during leaf constant period

Year	Mean LAI	Standard deviation	Maximum LAI	Minimum LAI
1996	5.22	0.39	6.05	3.90
1997	5.76	0.56	6.73	4.11
1998	7.08	0.46	8.41	5.61
1999	4.59	0.27	5.16	3.81
2000	6.65	0.59	8.09	5.44
2001	6.98	0.70	8.51	5.38

light absorption by the canopy, the model suggests LAI to vary around the maximum value. The normalized standard deviation (defined as the ratio of standard deviation to mean value) was as large as 10.0% in year 2001 (see Table 3). The noise in estimated LAI maximum could result from environmental influences on light penetration, e.g. factors that influence leaf orientation, as well as simplifications of the physical mechanism that are included into the model, e.g. time dependence of transmittance characteristics. This is discussed in detail below.

- c) Leaf production period (ca. Julian day 112 to 140): LAI rapidly increases from zero to the maximum value during this period. The initial changes in radiation absorption during this phase were well documented during 1997 and 2000 through 2002. Onset of LAI increase during 1996, 1998 and 1999 was estimated by extrapolation of the response curve to zero. This was included in order to compare LAI changes to changes in NEE. The relationship between LAI increase and change in ecosystem carbon exchange, especially in response to variation in climate, is extremely important to quantify, if we are to apply our site specific knowledge in the calculation of carbon balances for large areas. Surprisingly, shifts in the initial onset of LAI change were extremely small during the period of observation (Julian day 117 in 1997 vs. Julian day 120 in both 2000 and 2001).

We eliminated noise associated with short-term phenomena from the radiation absorption data by smoothing the observations before model application. We used two approaches: a Fast Fourier transform and a 5-day kernel convolution. The Fourier transformation technique repre-

sents the original data by the amplitudes of sine and/or cosine functions, which leave the 'true' or smoothed observations if appropriate criteria for separating the noise component from the total signal can be established. An algorithm that would do this could then be described as a low pass digital filter, since in most situations the noise is represented by the high frequency components. Since Fourier transformations requires a regular sampling within the temporal domain, which could not be fulfilled in this study due to missing or poor radiation measurements, the curves were fitted using the first four harmonics based on the least square method similar to the treatment of Sellers (1994) for NDVI, but setting the same weight to each observation. The underlying assumption here was that the residuals could be treated as noise for over 4 harmonics.

The estimated LAI agreed well with that obtained from litter collection (Fig. 3). Values for r^2 of 0.93, 0.95 and 0.97, respectively, were found for the direct model output of LAI using observations on each day, for the Fast Fourier transformed LAI, and convolve smoothed LAI. The corresponding RMSE were 0.56, 0.62 and 0.42.

3.3 Effects of weather conditions on model output

The radiation recorded by the under canopy sensor is the sum of direct and diffuse radiation that reaches the sensor through gaps in the canopy, and enhanced diffuse radiation due to multiple scattering of both the direct and diffuse radiation within the canopy. Under diffuse sky conditions, the multiple scattering inside the canopy is small, however under clear sky conditions, the sensor receives more diffuse radiation than that from the sky through canopy gaps (Welles and Norman, 1991). Since the model is applied on a daily basis and both radiation above and below the canopy are summed over the course of the day, it is to be expected that individual days will all be unique in terms of radiation transmission through the canopy. Moreover, leaf optical characteristics and leaf orientation may change under different environmental conditions and therefore affect the estimation of LAI.

In order to consider the relative importance of potential contributions to variation in model output during the leaf constant period, the LAI

variation ratio was defined as the ratio of the LAI deviation from the mean LAI value divided by the mean and was examined as a function of daily average temperature, VPD, and wind velocity, daily incoming global radiation, fraction of diffuse radiation in the total global radiation and precipitation. Except for precipitation, the relative LAI deviation was not significantly influenced by environmental factors. The relative LAI deviation is not dependent on differences in fraction of diffuse radiation in the total incoming radiation. A slight positive bias was observed with precipitation. Statistics revealed that 65% of cases with precipitation resulted in positive LAI deviation. One possible cause is that the over-canopy global radiation sensor is affected by precipitation and records less than normal radiation. An alternative explanation is that interception of precipitation alters leaf orientation in the canopy.

3.4 Comparison of MODIS LAI for the Hesse Forest site with ground-based LAI estimates

The MODIS LAI (MOD15, collection 004) at 1 km resolution in 2001 is used for comparison.

Though the assessment of LAI at different scales is not straightforward (Weiss et al., 2001), the MODIS LAI pattern expected for Hesse Forest over the annual cycle should resemble the modelled LAI output, especially since Hesse Forest is far larger than one km^2 pixel of MODIS data and relatively homogeneous. Tian et al. (2002) reported that coarse resolution LAI tended to be lower than values estimated at high resolution. The MODIS annual change in LAI for 2001 is depicted with convolve smoothed modelled LAI at the tower site in Fig. 4. The MODIS retrievals of LAI that are 8-day composites were successful in the sense, that in the summer, only one value was rejected by the quality check due to persisting adverse atmospheric conditions during the respective 8-day period. However, the MODIS LAI retrievals are lower during the leaf-constant period than the modelled LAI from ground data. While the MODIS LAI estimates from the backup-algorithm are at the lower border of the range of modelled LAI values, the LAI estimates from the radiative transfer algorithm (RT) are even lower and clear underestimates (cf. Knyazikhin et al., 1999 for details on algorithms). This is

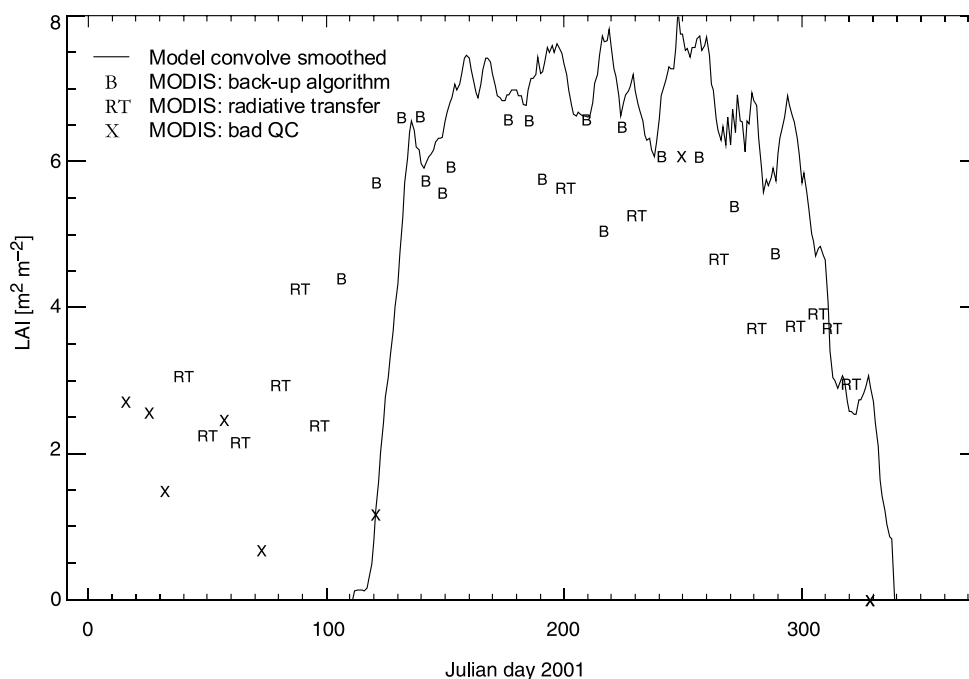


Fig. 4. Comparison of modelled LAI from ground observation with LAI retrievals from the MODIS sensor on Terra (MOD15A2, collection 004). It is indicated whether the radiative transfer algorithm (RT) or the empirical back-up method (B) was used for MODIS LAI retrieval, or if retrieval is considered invalid (X, e.g. cloudiness or sensor problems) according to MODIS quality control

surprising, since the latter is supposed to be under the best possible atmospheric conditions. Relatively large deviations are seen during winter and in spring before the leaf constant period, when MODIS tends to overestimate the LAI. While understory does not play a significant role at the Hesse site, it may well be, that the reflectance of the stems that are covered by algae (typical for Beech) confounds the spectral signature leading to overestimates of LAI by the algorithm. Also noteworthy is the trend of decreasing LAI in the MODIS data between julian day 200 and 280, that is not obvious in the modelled LAI from ground data and may be related the changes in the reflectance characteristics of the leaves themselves (while the overall transmittance that is used for the ground LAI remains constant). These issues clearly need further reconciling research.

3.5 Effect of leaf optical characteristics on model outputs

For the entire domain of shortwave radiation, leaves cannot be treated as ‘opaque’ as required by the gap theory applied in our model. A certain amount of radiation, especially in the near infrared, will be transmitted through the leaves and will arrive at the below-canopy radiation sensor. Neglect of this effect will lead to an underestimation of LAI. This is the physical basis for including the leaf transmittance τ_l in Eq. (12). Thus, accurate determinations of leaf transmittance

τ_l will have an important influence on final predicted LAI. Sensitivity analysis of predicted LAI to changes in leaf transmittance indicated that a 10% over- or under-estimation of leaf transmittance will lead to 2.8% change in predicted LAI and that the effect is approximately linear with further changes in transmittance. A 10% change in transmittance is equal to 0.21 shift in LAI during the leaf constant period when maximum LAI value is ca. 7.4. Leaf optical characteristics are determined by the concentration pigments, water, nitrogen, cellulose, and lignin together with leaf structure (Dawson et al., 1998). The constituents do change over time and modify leaf transmittance. The assumption in the model that leaf transmittance is constant is one factor that probably contributes to predicted LAI change during the leaf constant period.

3.6 Daily and seasonal variation of extinction coefficient k

Predicted daily and seasonal influences on the extinction coefficient k are illustrated in Fig. 5. The daily courses of the extinction coefficient k are predicted according to these methods as being symmetrical around solar noon, when the lowest values occur. Higher values of the extinction coefficient during early and late hours of the day are largest near the winter solstice when sun angles are low. Thus, the lowest value of the extinction coefficient k is 0.35 at the solar noon

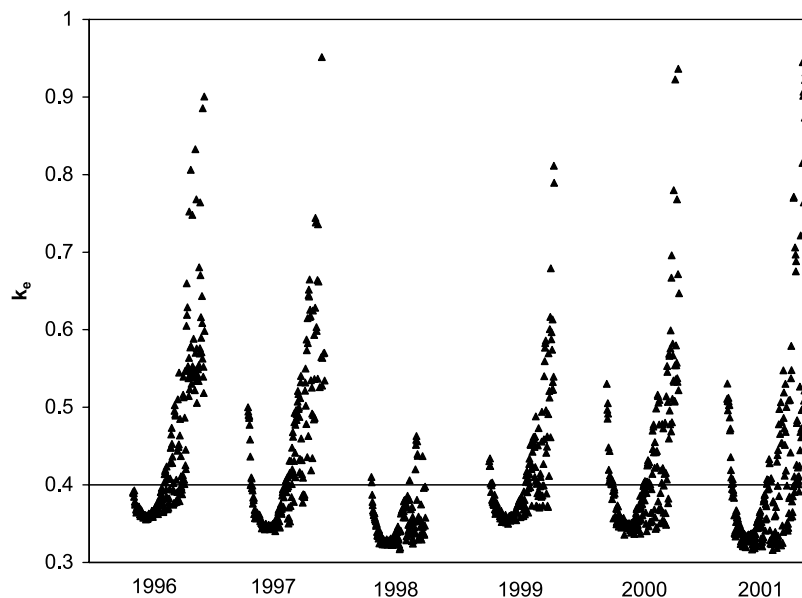


Fig. 5. Effective extinction coefficient k_e derived from the Beer-Lambert law using the model output LAI. The line of 0.4 refers to the constant value applied by Granier et al. (2000)

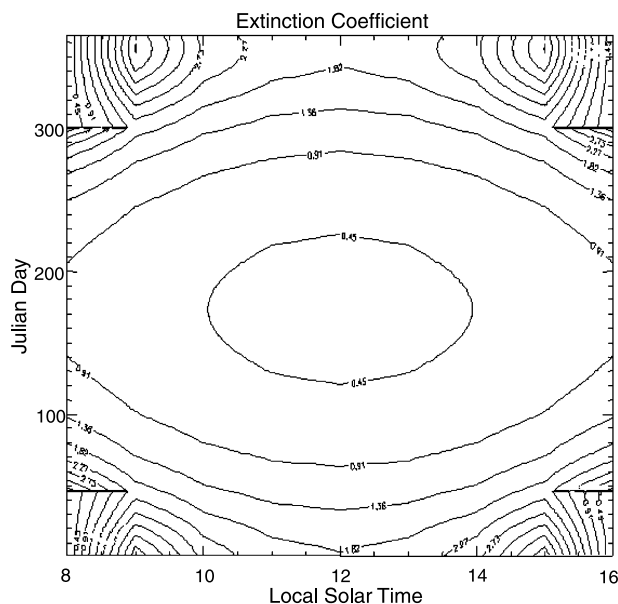


Fig. 6. Contour line of extinction coefficient k at the domains of Julian day and local solar time (hour)

of the summer solstice, while the largest is 4.56 at the largest solar zenith angle of the day on winter solstice. The variation range from our model is larger than suggested by Jarvis and Leverenz (1983) for broadleaf forest. Symmetric seasonal courses similarly occur for each solar time with the lowest value at solar noon and increase with increasing solar zenith angle. The extinction coefficient k at solar noon varies from 0.35 (the lowest value, summer solstice) to 1.882 (the largest value, winter solstice).

The daily and seasonal variations in the extinction coefficient must be considered when applying the Beer-Lambert law as a simple approximation for canopy radiation absorption. For compatibility between LAI estimated by the model and appropriate radiation absorption, effective extinction coefficients such as those shown in Fig. 6 must be used. In previous work, Granier et al. (2000) set the extinction coefficient as a constant of 0.4. The assumption underestimates the LAI during the middle of the year, while an overestimate of LAI occurs during leaf flushing and during the senescence period.

4. Conclusions

LAI is an important input to gas flux models in order to simulate the annual course of carbon and water fluxes. Due to the difficulty or the laborious

work involved in direct measurements of LAI, this phenology dependent parameter has usually been treated in simplified fashion. The paper presents a model to estimate LAI based on the daily above- and below-canopy global radiation.

Six continuous yearly LAI curves (from 1996 to 2001) were simulated through the above- and below-canopy radiation measurements based. The performance of this model was tested against *in situ* measurement by DEMON and litter collection in Hesse forest. The output agreed well with litter collection data over the years. The model output was stable during “leaf production” and “leaf senescent” periods but exhibited obvious variation during “leaf constant period”. The analysis of relative variation ratio with environmental parameters revealed that precipitation had an important effect on the variation. To remove the noise, Fast Fourier transform and convolve methods were applied to smooth the LAI data to form the LAI curves.

Leaf transmittance played an important role in the model output accuracy. The sensitivity analysis indicated that 10% uncertainty in leaf transmittance would lead to 2.8% variation of LAI. The extinction coefficient k varies at both daily and seasonal scales. This leads to large deviations of LAI if directly derived using Lambert-Beer law (treating the extinction coefficient k as a constant value) to calculate LAI. The comparison of MODIS LAI data for the tower site pixel in the year 2001 with convolve smoothed LAI curve showed a large deviation from MODIS LAI before the “leaf constant” period. A similar pattern but with underestimated LAI values was found during the “leaf constant” period. Therefore, the direct application of MODIS LAI in deciduous forest still requires much caution.

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Appendix

The sunrise time angle ω_s is determined by:

$$\omega_s = \arccos(-\tan \varphi \tan \delta) \quad (\text{A1})$$

where φ is latitude and δ is the declination angle (the angular position of the sun at solar noon with respect to the plane of the equator) which is calculated as:

$$\begin{aligned} \delta = & (0.006918 - 0.399912 \cos(\Gamma) + 0.070257 \sin(\Gamma) \\ & - 0.002697 \cos(2\Gamma) + 0.000907 \sin(2\Gamma) \\ & - 0.002697 \cos(3\Gamma) + 0.00148 \sin(3\Gamma)) \times \left(\frac{180}{\pi}\right) \end{aligned} \quad (\text{A2})$$

where Γ is the day angle from:

$$\Gamma = \frac{1}{365} (2\pi(J - 1)) \quad (\text{A3})$$

and J is the Julian day.

The instantaneous potential solar radiation is calculated as:

$$S_0 = I_0 E_0 \cos \theta \quad (\text{A4})$$

where I_0 is the solar constant ($4.921 \text{ MJ m}^{-2} \cdot \text{hour}^{-1}$) and E_0 is the eccentricity of the earth's orbit determined by:

$$E_0 = \left(\frac{d_0}{d}\right)^2 = 1 + 0.033 \cos\left(\frac{2J}{365}\right) \quad (\text{A5})$$

where d_0 is the mean sun-earth distance ($1.496 \times 10^8 \text{ km}$), while d is the actual sun-earth distance.

The potential daily radiation received by a horizontal surface then can be integrated as:

$$S_{0,d} = \int_D S_0 \quad (\text{A6})$$

D denotes the domain of day length in hours as:

$$D = 2 * \arccos(-\tan \varphi * \tan \delta) \quad (\text{A7})$$

The potential daily radiation can also be calculated by

$$S_{0,d} = \left(\frac{24}{\pi}\right) I_0 E_0 [\omega_s \sin \varphi \sin \delta + \cos \varphi \cos \delta \sin \omega_s] \quad (\text{A8})$$

For a given local time t , the sun zenith angle can be calculated from the sun orbital equation:

$$\cos \theta = \sin \varphi \sin \delta + \cos \varphi \cos \delta \cos \omega \quad (\text{A9})$$

where ω is hour angle corresponding to local time t (in radians)

$$\omega = (12 - t) * \frac{\pi}{12} \quad (\text{A10})$$

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