Tree scale distributed multipoint measuring system of photosynthetically active radiation

L. Palva a,*, T. Markkanen b, E. Siivola a, E. Garam a, M. Linnavuo a, S. Nevas d, F. Manoochehri d, S. Palmroth c, K. Rajala a, H. Ruotoistenmäki a, T. Vuorivirta a, I. Seppälä a, T. Vesala b, P. Hari c, R. Sepponen a

a Applied Electronics Laboratory, Helsinki University of Technology, P.O. Box 3000, FIN-02015 HUT, Finland
b Department of Physics, University of Helsinki, P.O. Box 9, FIN-00014 University of Helsinki, Finland
c Department of Forest Ecology, University of Helsinki, P.O. Box 24, FIN-00014 University of Helsinki, Finland
d Metrology Research Institute, Helsinki University of Technology, P.O. Box 3000, FIN-02015 HUT, Finland

Received 31 March 2000; received in revised form 13 June 2000

Abstract

A tree scale distributed multipoint measuring system of photosynthetically active radiation (PAR) has been designed. The system is divided into a central unit, measuring units and sensor–amplifiers. Measurements can be carried out with a maximum number of 32 measuring units each comprising 24 sensor–amplifiers. The feasibility of the system has been demonstrated with measurements within a Scots pine canopy using a 12 m telescopic mast with horizontal cross-booms. Two sensor arrays of 4 m in length comprising about 40 sensors were divided into 10-sensor sub-arrays of 1, 2, and 4 m in length. The simultaneously measured PAR averages over the sub-arrays differed considerably from the 4 m reference arrays. The maximum difference was 100% in the case of the 1 m sub-arrays, 80% in the case of the 2 m sub-arrays and 54% in the case of the 4 m sub-arrays. When averaged over the 6 h measuring period around noon, the respective maximum differences were 27, 15 and 3%. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Multipoint measuring system; Photosynthetically active radiation; Sensor; Photodiode; Data acquisition; Scots pine

1. Introduction

Within a forest canopy the availability of PAR (400–700 nm) is determined by the type and characteristics of the forest. Moreover, the spatial distribution of PAR depends on the depth within the canopy (Baldocchi et al., 1986; Ross et al., 1998). In photosynthetic studies, this distribution is needed due the nonlinear dependency of the photosynthetic rate on PAR (Norman and Jarvis, 1974; Sheehy and Chapas, 1976; Hari et al., 1984; Baldocchi et al., 1986; Myneni et al., 1989; Pearcy, 1989). Therefore, to assess the photosynthetic productivity of a heterogeneous forest canopy, measurements of PAR at different depths within the canopy are needed.

Various methods have been used for estimating PAR within canopies depending on the specific requirements of the study, such as the spatial scale of the site (Baldocchi and Collineau, 1994). Reifsnyder et al. (1971) determined statistical guidelines for the measurement of solar radiation within a pine canopy using 15 pairs of sensors at randomly located...
measuring points in a semicircle having a radius of about 30 m. It was concluded that within pine canopies, about 400 sensors would be required to estimate the mean value of the direct component of instantaneous radiation. However, fewer sensors are needed for longer averaging periods. For example, Gay et al. (1971) used five sensors in a grid with about 8 m between the measuring points, and recommended that beneath a pine canopy on a cloudless day five sensors would be required to determine the daily mean of the transmitted total radiation. In general, the number of measuring points needed has been found to depend on the type of canopy and on the duration of the measuring period (Reifsnyder et al., 1971; Baldocchi and Collineau, 1994).

In studies where a high number of measuring points has been required, mobile sensors have often been used for the measurement of the spatial distribution of radiation (Mukammal, 1971; Norman and Jarvis, 1974; Sinclair and Knoerr, 1982; Baldocchi et al., 1986; Péch, 1986; Cohen and Fuchs, 1987; Ross et al., 1998). The sensor or a number of sensors are mounted on a carriage which traverses along a track of about 1 m to tens of meters in length. Although a moving sensor has advantages (see, e.g. Brown, 1973; Péch, 1986) there is, however, problems in the case that the separation of spatial and temporal components of PAR variability is required (Baldocchi and Collineau, 1994). For this purpose, simultaneous measurements with a representative number of sensors are preferred (Salminen et al., 1983; Gutschik et al., 1985).

The dependence of the measuring accuracy on the number and spatial distribution of measuring points has been studied within a Scots pine canopy in a case where the spatial scale was the area of a twig (Palva, 1998; Palva et al., 1998). A fiberoptic sensor comprising 400 measuring points in a regular grid of 11 cm × 20 cm was used. The results showed that the spatial distribution of the measuring points is of major importance. For example, in a case where 192 measuring points covering the needle region and 24 evenly distributed points were selected, these 24 points provided a maximum difference of 3% from the value obtained using the 192 points. However, in the case where the 96 points covering half of the needle region were selected, the maximum difference was 20%.

The aim of this study was to develop a multipoint measuring system of PAR specified for tree scale assessments of PAR distributions within a forest canopy. In this paper, the measuring system is described in detail, the sensor is characterised and the system is used to investigate the effect of the number and the spatial distribution of measuring points in determining the average PAR in the mid crown and close to the crown base within a Scots pine (Pinus sylvestris L.) stand.

2. Methods

2.1. Construction of the measuring system of photosynthetically active radiation

2.1.1. General view

The measuring system is divided into a central unit (CU), measuring units (MU) and sensor–amplifiers (SA). The MUs are connected with a serial communications line and to a common power supply. The construction enables measurements with a maximum number of 32 MUs each comprising 24 SA. Thus, 768 (32 × 24) sensors can be employed which correspond to the indications given by studies of Reifsnyder et al. (1971) and Palva (1998).

The system is movable and capable of long term automatic data collection. The connection network enables the distribution of MUs into chain and star-type arrangements with a maximum cable length of 100 m. The sensor–amplifiers have a maximum cable length of 5 m. Measurement configurations are alterable with respect to the measuring point number, spatial resolution of measurements with a minimum distance of 10 mm between the 1.6 mm² measuring points and the arrangement of MUs into groups with a variable number and spatial positioning.

2.1.2. Data acquisition and processing

An industrial PC104-standard microcomputer (MSM386SV, Digital-logic, Switzerland) functions as the CU taking care of the system timing and data storage. A measuring unit consist of a single chip microcontroller (Intel 87C51, Intel, USA) 24-channel analog multiplexer (CD4051, Texas Instruments, USA), eight-bit analog to digital converter (TLC549, TI, USA) and RS-485 transceiver (75180, TI, USA). The MUs are controlled by the CU with addressed messages via an RS-485 serial communication line. In case a measuring unit receives a data request
command, a sequential sampling procedure covering the 24 channels in a time of 1 m s is followed. Thereafter, the resulting datapacket is transmitted to the CU in 40 m s. The data transfer rate is 9600 bit s⁻¹.

2.1.3. Sensor–amplifier

Quantum sensors are commonly used for the measurement of PAR (Pearcy, 1989). A conventional quantum sensor comprises a photodiode and optical filters in a hermetically sealed housing with a diffuser placed on the top to provide a cosine response. As an affordable alternative photodiodes have been used in multipoint measuring systems (Gutschik et al., 1985; Chazdon and Field, 1987). The applicability of photodiodes for PAR measurements has been discussed by Pearcy (1989).

The selected sensors were silicon photodiodes with IR filters (VTB 9412B, EG&G Vactec Optoelectronics, USA). The sensor–amplifier construction is shown in the diagram of Fig. 1. Important characteristics of the selected photodiode and the operational amplifier (TLC271ID, Texas Instruments, USA) are presented in Table 1. The measurement bandwidth determined by the time constant of the transimpedance $R_1C_1$ is 160 Hz and the absolute response of the sensor–amplifier combination is of the order of 150 μA (3 V)/2000 μmol m⁻² s⁻¹. In comparison to the absolute response, the amplifier bias current and offset voltage as well as the photodiode dark current are negligible (Table 1). In order to prevent environmental effects, the electrical circuitry is sealed with epoxy resin (EER2001RP250G, Electrolube, UK).

2.2. Measurements of sensor characteristics

Since only the peak value of the spectral response and the half power angle of the angular response of the photodiode were given by the manufacturer, measurements were carried out to obtain these characteristics more comprehensively.

2.2.1. Spectral response

The spectral response measurements were performed using a single-beam reference spectrometer for the wavelength range 300–820 nm and the trap detector MRI-9402 was used as the reference detector (Manoochehri et al., 1999). The responses of the detectors were measured by interchangeably placing each detector in the beam. The 5 mm diameter beam completely covered the test photodiode. After subtraction of the dark signals, the ratio of the photodiode response to that of the reference detector was calculated at each wavelength. The known spectral response of the reference detector was finally used to determine the relative spectral response of the photodiode. The response curve is shown in Fig. 2a.
2.2.2. Angular response

The measurements of the relative angular response of the test photodiode were made using a 1000 W quartz–tungsten–halogen (QTH) lamp as a light source. The lamp and the photodiode were mounted on an optical rail and were aligned on the optical axis by using an alignment laser. The distance between the light source and the photodiode was 1.5 m. Two baffles were used to reduce the effect of the scattered light. The angle of incidence of the light beam onto the photodiode was alternated by using a high-accuracy rotating table. The photodiode was mounted on the rotating table so that the axis of rotation was through the center of the active area. Three measurement runs of the relative angular response of the photodiode were performed. The step angle was 2° and the range of angle was from 0 to ±90°. The ratio of the readings and the cosine response in relative values is shown in Fig. 2b.

![Image of photodiode sensor characteristics](image)

Fig. 2. Measured characteristics of photodiode sensor (a) relative spectral response and (b) relative deviation of angular response from cosine response.

2.3. Calibration

The sensors were calibrated in sunlight using quantum sensor LI-190SA with an LI-190SB millivolt adapter (LI-COR Ltd., NE, USA) as a reference. An absolute response of 10 mV/2000 μmol m⁻² s⁻¹ is given with a 5% uncertainty for the reference sensor. Because of deviations in the responsivities between the measuring channels, a correction factor was given to each channel. The calibration was checked after a 4-month period of measurements within the canopy and 6 months in store. The average difference between the correction factors was 3.6% and standard deviation was 3.2%. Long term stability of sensors with similar characteristics has been reported, e.g. by (Aaslyng et al., 1999). Cosine correction for direct radiation was performed as follows. The proportion of direct radiation $I_{sh}$ was modeled by

$$I_{sh} = S_0 \tau^m \sin(\gamma_s),$$  \hspace{1cm} (1)

where $S_0$ denotes PAR equivalent of the solar constant=2700 μmol m⁻² s⁻¹ (Weiss and Norman, 1985), $m=1/\sin(\gamma_s)$ the air mass, $\tau^m$ the atmospheric transmittance of direct radiation in clear sky conditions (Gates, 1980) and $\gamma_s$ denotes the sun elevation angle. The proportion of diffuse radiation $I_{dh}$ was modeled by

$$I_{dh} = \alpha [\beta S_0 \sin(\gamma_s) - I_{sh}],$$  \hspace{1cm} (2)

where $\alpha$ and $\beta$ are parameters. The values used for $\alpha$ and $\beta$ were 0.5 and 0.91, respectively (see Campbell, 1981). The diffuse radiation field inside the canopy was assumed to be homogeneous and it was assumed to decrease as a function of the cumulative leaf area index $L$ according to the Beer’s law

$$I_{dh}(L) = I_{dh}(0) e^{-kL},$$  \hspace{1cm} (3)

where $k$ is an extinction coefficient. The value 0.19 for $k$ was determined from the measurements during cloudy periods. The proportion of diffuse radiation was subtracted from PAR readings and the remainder, which was assumed to be the share of direct radiation at each measuring point, was corrected by the measured sensor deviation from the cosine response corresponding to the sun elevation angle.
2.4. Mechanical structure

A telescopic mast with cross-booms has been implemented providing variable measurement set-ups and lightweight constructions to facilitate transferability and ease in setting up the system. The height of the mast is adjustable within 6–12 m and the maximum length of the booms of aluminum rectangle-profile is 5 m. The booms can be positioned on the mast freely except for a minimum distance of 25 cm between adjacent booms. One arrangement for PAR measurements is shown in Fig. 3.

2.5. Field measurements

2.5.1. Site

The measurements were carried out within a 35 year old Scots pine stand with an average tree height of 13 m and a total leaf area index of nine at the SMEAR II field measurement station (Station for Measuring Forest Ecosystem–Atmosphere Relations), which is located in Hyytiälä, Southern Finland (61°51’N, 24°17’E, 175 m a.s.l.) (see Vesala et al., 1998). The stand is homogeneous for about 200 m in all directions from the measurement site, extending approximately 1.2 km to the north (60° zone). The terrain is subject to modest height variation. The wood biomass is 47 tons per ha and the tree density is 2500 ha⁻¹.

2.5.2. PAR measurements

The mast was erected in the middle of the stand and the sensor array was laid out in a north–south direction. The booms were 5, 4 and 2 m long. The main part of the sensors was placed symmetrically on both sides of the mast with 0.1 m distance between each sensor. The remainder of the sensors were placed in sets of 4–6 sensors at 1 cm distances in three of the booms as shown in Fig. 3. On top of the mast at 12 m there were four sensors for measuring PAR above the canopy. A sunny day 26 June was selected for the analysis. This analysis includes measurements between 9.00 a.m. and 3.00 p.m. recorded every 7 s.

3. Results and discussion

3.1. Spatial variation

Two 48-sensor booms, the 5 m long boom at 6.6 m close to the crown base and the 4 m long boom at 8.6 m in the mid part of the crown, were selected. Characteristics of horizontal variability at the two heights can be seen in Fig. 4 where examples of instantaneous PAR measurements at 10.00, 12.00 and 14.00 h are presented as a function of the distance. Point by point measurements show sensors in full shade, partial sun and full sun with great differences up to 30 times in magnitude between the ones in the shade and in the sun. Differences of similar or even greater magnitude order have been obtained, e.g. by Cohen and Fuchs (1987) with a moving sensor on a 12 m track below a hedgerow canopy and Ross et al. (1998) in a willow coppice using a moving sensor on a 6 m track. Examples of frequency distributions of three 10 min periods of PAR measurements beginning at 9.50, 11.50 and 13.50 h at the two heights are presented in Fig. 5. During all included periods the shape of the frequency distribution is negatively skewed at the crown base while bimodal skewness is observed within the crown.
Fig. 4. Instantaneous point by point measurements of PAR at (a) 6.6 m and (b) 8.6 m. Dotted line denotes instantaneous average PAR obtained with four sensors on top of the mast. Measurements: 10.00, 12.00 and 14.00 h, 26 June 1998.

These observations are of similar character to those obtained by, e.g. Baldocchi et al. (1986) between 12.00 and 13.00 h using moving sensors along 30 m horizontal transects at several heights in an oak hickory forest. During the measuring periods, the average PAR

Fig. 5. Frequency distributions of instantaneous PAR measurements at (a) 6.6 m and (b) 8.6 m. Measurements: 9.50–10.00, 11.50–12.00 and 13.50–14.00 h, 26 June 1998.
Fig. 6. Relative deviations of average PAR obtained with a variable number of sensors (N) from average PAR with maximum number of sensors (a) at 6.6 m and (b) at 8.6 m. Deviations are in absolute values. Curved line represents fit of function f(N) in mean value of deviations. Measurements: 9.00–15.00h, 26 June 1998.

of the instantaneous measurements ranged from 280 to 470 µmol m\(^{-2}\) s\(^{-1}\) and the standard deviation from 330 to 440 µmol m\(^{-2}\) s\(^{-1}\) at 6.6 m, and for 8.6 m these ranges were 850–1100 and 560–690 µmol m\(^{-2}\) s\(^{-1}\).

3.2. Number and distribution of measuring points

The effect of the number and distribution of the measuring points on the estimation of the average PAR was evaluated. The two 48-sensor booms were analyzed separately. Only the sensors at 10 cm spacing were included in this analysis resulting in a maximum number of 41 sensors at 6.6 m and 36 sensors at 8.6 m. In the following analysis, PAR\(_{\text{ave}}\) denotes the average of PAR obtained with various number of sensors and PAR\(_{\text{ref}}\) denotes the average PAR obtained by using the maximum number of sensors.

The importance of the measuring point number was studied by selecting a variable number (N) of measuring points with even distances of maximum length between the measuring points for calculating PAR\(_{\text{ave}}\). Relative deviations of PAR\(_{\text{ave}}\) from PAR\(_{\text{ref}}\) are presented in absolute values as a function of N in Fig. 6. A single measuring point was excluded from the fit of the function f(N)=N\(^{-a}\)×b in the mean value of the deviations since the position of a single sensor in the boom had a considerable effect on the values of the parameters a and b obtained by this fit.

To study the effect of the distribution of measuring points in determining PAR\(_{\text{ave}}\), the sensor arrays of the two booms were divided into sub-arrays of 1, 2 and 4 m in length as shown in Fig. 7. Ten measuring points with even distances were selected from each of these sub-arrays. Fig. 8 shows how the values of PAR\(_{\text{ave}}\) corresponding to these arrays deviate from the values of PAR\(_{\text{ref}}\). Deviations of the instantaneous measurements are plotted by the columns containing 50% of the values and the average of the deviations calculated over the whole 6 h measuring period are marked by a point in the columns. In the case of the instantaneous measurements, the values of PAR\(_{\text{ave}}\) obtained with the 1 m sub-arrays differ from the values of PAR\(_{\text{ref}}\) by 100% at a maximum, in the case of the 2 m sub-arrays the maximum difference is 80% and for the 4 m sub-arrays
Fig. 8. Relative deviations of average PAR obtained with 1, 2 and 4 m 10-sensor sub-arrays from average PAR with maximum number of sensors at (a) 6.6 m and (b) 8.6 m. Columns include 50% of the values of the instantaneous measurements, medians of measuring periods are denoted by transverse lines and averages over measuring period 9.00–15.00 h are denoted by points. Measurements: 9.00–15.00 h, 26 June 1998.

Correlations of instantaneous measurements between each pair of sensors over the period 11.00–14.00 h were calculated. In Fig. 9, the averaged correlation values are presented as a function of the distance between the sensors. In this study, also the sensors at 1 cm spacings were included. Already at the 1 cm spacings there is large variability in the values of the correlation coefficients ranging from 0.9 to −0.2 at 8.6 m and at 1 m distances the average of the coefficients settles around zero at both heights. These observations are parallel with the results obtained in earlier studies within a 20 year old Scots pine stand where spatial correlation was investigated with an array of 19 sensors at 1.5 cm distances located below

the maximum difference is 54%. It can be noted from Fig. 8 that some of the columns corresponding to the 1 and 2 m sub-arrays are positioned entirely above and some are positioned entirely below the point of the zero deviation. For example, the column corresponding to sub-array B2 is above the zero deviation point, which means that the values of \( \text{PAR}_{\text{ave}} \) were mainly higher than \( \text{PAR}_{\text{ref}} \). As a consequence, \( \text{PAR}_{\text{ave}} \) averaged over the 6 h measuring period differed considerably, by 27%, from \( \text{PAR}_{\text{ref}} \). In the case of the 2 m sub-arrays, the temporal averaging provided a maximum difference of 15% between \( \text{PAR}_{\text{ave}} \) and \( \text{PAR}_{\text{ref}} \) and in the case of 4 m sub-arrays the maximum difference was as low as 3%.

Fig. 9. Correlations between sensor readings as a function of distance at (a) 6.6 m and (b) 8.6 m. The correlations of the instantaneous measurements are within vertical lines and averages over measuring period 11.00–14.00 h are denoted by points. Measurements 11.00–14.00 h, 26 June 1998.
crown base (Smolander, 1984). In those measurements, the correlation coefficient became negative after a distance of 18 cm with 5 min averaging periods. In the present study, the negative values appear at such close distances that there is obviously a need for higher measurement resolution to obtain a more detailed analysis.

4. Concluding remarks

A flexible multipoint measuring system of photosynthetically active radiation (PAR) has been designed and operated within a Scots pine canopy. This system provides a tool for versatile studies of PAR characteristics within tree dimensions with a maximum number of 32 measuring units of 24 sensor–amplifiers. The measuring units connected with a common serial communications line can be synchronized for measurements within a 20 ms time window. The 24-sensor sampling sequence of a single measuring unit takes about 1 ms. With the used set-up of 168 sensors recorded every 7 s, the system is capable of continuous data collection over a 3-week period. Measurement configurations are alterable with respect to the measuring point number, spatial distribution of measurements with minimum distance of 10 mm between the 1.6 mm² measuring points and arrangements of measuring units into groups with a variable number and spatial positioning. The whole system is also easily relocated.

The usefulness of the system has been demonstrated with field measurements. The first measurements within a Scots pine canopy have already been reported in a previous study dealing with the effect of spatial and temporal averaging of PAR measurements in estimating the CO₂ exchange (Vesala et al., 2000). In this study, the effect of the number and distribution of the measuring points on the estimation of the average PAR was analyzed with a boom at 6.6 m close to the crown base and another at 8.6 m in the mid part of the crown. Two sensor arrays of 4 m in length comprising about 40 sensors were divided into 10-sensor sub-arrays of 1, 2 and 4 m in length. Simultaneously, measured PAR averages over the sub-arrays differed considerably from the 4 m reference arrays. The maximum difference was 100% in the case of the 1 m sub-arrays, 80% in the case of the 2 m sub-arrays and 54% in the case of the 4 m sub-arrays. When averaged over the 6 h measuring period around noon, the respective maximum differences were 27, 15 and 3%.

In this study, we have introduced a new tool for measuring spatial and temporal characteristics of PAR within canopies. The system may be adapted to various measurement situations. The first results demonstrate the feasibility of the distributed tree scale multipoint measuring system.

References


