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SHORT COMMUNICATION

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The applicability of a color acetate film for estimating photosynthetic photon flux density in a forest understory

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Abstract The suitability of a color acetate film for estimating photosynthetic photon flux density (PPFD) in a forest understory was examined. The fading ratio of the film (F), the total PPFD ($PPFD_{total}$) to which the film was exposed, and the average daily maximum temperature during exposure (T) were obtained from measurements at multiple sampling points throughout an entire year within a natural secondary forest ($n = 42$). The ranges of the recorded values were as follows: F 35%–99%, $PPFD_{total}$ 1.4–28.3 mol m^{-2}, and T 6°–32°C. $PPFD_{total}$ was regressed by F and T with a high r^2 (=0.94; $P < 0.0001$): $PPFD_{total} = (100 - F)/(1.085 + 0.051\,T)$. The absolute error (|estimated $PPFD_{total}$ − measured $PPFD_{total}$|) averaged 1.3 mol m^{-2} with a maximum of 5.7 mol m^{-2}, indicating a good fit. These results indicated broad applicability of the film, both spatially and temporally, for estimating forest understory PPFD.

Key words Color acetate film · Light measurement · PPFD · Forest understory

Introduction

Assessments of photosynthetic photon flux density (PPFD) provide important information about the growing conditions of forest understory plants. Direct measurements using quantum sensors can be effective, but these devices are expensive, cumbersome, and impractical for multiple-point sampling. Simple, indirect methods for accurately estimating PPFD in the forest understory are needed.

A color acetate film (R-2D, Taisei Chemical Industries, Tokyo, Japan) is useful. The film is impregnated with azo dyes and fades as the dyes are decomposed by exposure to sunlight (Yoshimura et al. 1989). Fukushima (1998) confirmed that the fading of the film was highly correlated with the integrated PPFD in a forest understory, although the study was limited to a single sampling point during 1 month of the year.

The spectral sensitivity of the color film is maximal in the green light band (521 nm, Yoshimura et al. 1989), so it does not exactly correspond with that of the quantum sensor (400–700 nm). As leaves can act as a spectral filter, the spectrum of light under the forest canopy varies with canopy structure and density (Muraoka et al. 2001). Owing to differences in the spectral sensitivities of the film and the quantum sensor, the relationship between the fading of the film and the integrated PPFD measured using the sensor can vary even within a forest. Hence, if film is used at multiple points in a forest understory, we may need to establish a general relationship between the fading of the film and the integrated PPFD, including the possible variation across sampling points. In addition, because the fading reaction of the film depends on temperature (Yoshimura et al. 1989; Akiyama et al. 2000; Fukushima 2000), we should correct for the effect of temperature if film is used year-round. In this study, to confirm the broad applicability of film as a tool for estimating PPFD in forest understory, we examined the relation of fading of the film, temperature, and the integrated PPFD based on data obtained at multiple points throughout an entire year in a natural secondary forest.

Materials and methods

Study site

The study was conducted in a natural secondary forest at the Kamigamo Experimental Forest Station of Kyoto University (35°04′N, 135°46′E; altitude 150 m asl), Japan. A 15 × 20-m plot was established in the forest. The density of overstory trees [diameter at breast height (DBH) ≧5 cm]

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was 1600 trees/ha; the mean DBH was 11.1 cm; and the mean height was 8.2 m. The dominant species were the evergreen trees *Ilex pedunculosa* Miq. and *Chamaecyparis obtusa* Endl., while there were some deciduous trees, such as *Quercus serrata* Thunb. ex Murray. The density of subcanopy and understory trees (with DBH < 5 cm and height > 0.5 m) was 10433 trees/ha. Species of Ericaceae (*Rhododendron macrosepalum* Maxim. and *Lyonia ovalifolia* Drude var. *elliptica* Hand.-Mazz.) and Theaceae (*Eurya japonica* Thunb. and *Cleyera japonica* Thunb.) were dominant.

Color acetate film

Color acetate films impregnated with azo dyes (R-2D, Taisei, Tokyo, Japan) that fade as solar radiation is absorbed were used in the study. The optical transmittance (O) of the film was determined using a portable photometer (THS470, Taisei). The absorbance (D) of the film was calculated from the transmittance, O, as follows:

$$D = a + b\left[-\log\left(O/100\right)\right] \tag{1}$$

where a and b are meter-specific constants ($a = -0.2683$, $b = 1.7456$). From the absorbance of the film before use (D_0) and after exposure (D), the fading ratio (F) as calculated using the following formula:

$$F = 100\left(D/D_0\right) \tag{2}$$

Field measurements

Two films were put on the side of a quantum sensor (LI-190SA, Li-Cor, Lincoln, NE, USA), which was then placed at a sampling point in the understory of the established plot. The sensor was connected to a datalogger (LIT-DR 190SZ-7600, Hoga, Kyoto, Japan), and instantaneous PPFDs were recorded at 2-min intervals. The measurements were collected for 7–10 days, and subsequently the absorbances of the film after exposure (D) were determined. These measurements were conducted repeatedly between March 2003 and March 2004 (1–4 points per month). The sampling points were arbitrarily located 1–3 m above the ground within the plot (15×20 m), e.g., under canopy gaps, beneath closed canopy, or within tree crowns, to include a wide range of light quality environments. A total of 42 points were sampled.

Data analysis

The fading ratio (F) was calculated for each film using the absorbance of the film before use (D_0) and after exposure (D) (Eqs. 1, 2). The total PPFD ($PPFD_{total}$, $mol\,m^{-2}$) during the exposure period was calculated as the integral of the instantaneous PPFD recorded by the sensor.

We assumed the following relationship between F and $PPFD_{total}$:

$$F = -K\left(PPFD_{total}\right) + 100 \tag{3}$$

where K is a reaction rate constant. The constant K changes with temperature (Yoshimura et al. 1989), because the fading rate of each dye is dependent on temperature. To characterize the change of K with temperature, we assumed the following relationship:

$$K = v + wT \tag{4}$$

where v and w are constants, and T is the average daily maximum temperature during the measurement period. Daily records of maximum temperature were obtained from the Kamigamo Experimental Forest Station.

Note that according to a preliminary analysis of our data, the linear functions (Eqs. 3 and 4) had higher coefficients of determination than previously used nonlinear functions, such as exponential (Yoshimura et al. 1989; Fukushima 2000) or second-order polynomial (Akiyama et al. 2000) functions. The choice of function to characterize the relationship of $PPFD_{total}$ of F and T should be examined in each study.

From Eqs. 3 and 4, the following regression of $PPFD_{total}$ on F and T was calculated:

$$PPFD_{total} = \left(100 - F\right)/\left(v + wT\right) \tag{5}$$

Parameters v and w, and the coefficient of determination, r^2, were estimated using the Quasi-Newton method with nonlinear least squares (SYSTAT 1992). The estimated $PPFD_{total}$ was then calculated using Eq. 5, the estimated values of v and w, and the measured values of F and T, for each measurement. The relationship of the estimated $PPFD_{total}$ to the $PPFD_{total}$ measured directly using the quantum sensor was examined to validate the applicability of films for estimating $PPFD_{total}$ in a forest understory.

Results

For the 42 measurements, the ranges of the recorded values were as follows: F 35%–99%, $PPFD_{total}$ 1.4–28.3 $mol\,m^{-2}$, and T 6°–32°C. The difference in F between the two films in each measurement averaged 2.1% (SD = 2.9). The daily $PPFD_{total}$ on days with clear skies averaged 1.7 $mol\,m^{-2}$ (range 0.2–4.8 $mol\,m^{-2}$).

Figure 1 shows the plot of F against $PPFD_{total}$. The data are categorized into two classes of T and the data for these two classes are segregated. At a given $PPFD_{total}$, F was smaller in the high temperature class, indicating that high temperatures accelerated the rate of film fading. When $PPFD_{total}$ was regressed by $(100 - F)/K$, and the effect of temperature was not included (i.e., K is constant), the coefficient of determination (r^2) was 0.84. The error of estimation (i.e., estimated $PPFD_{total}$ − measured $PPFD_{total}$) was significantly positively correlated with T (Error = $0.29\,T - 6.75$; $r = 0.74$; $P < 0.0001$).

Using Eq. 5, we regressed $PPFD_{total}$ on F including the effects of T as follows:

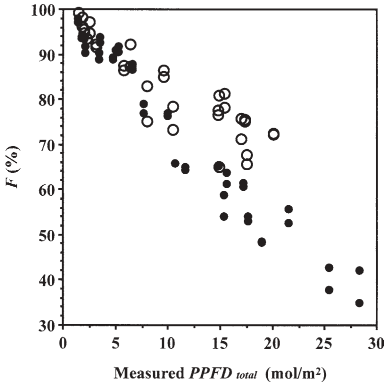

Fig. 1. The relationship between the fading ratio (F) of color acetate film and the total photosynthetic photon flux density ($PPFD_{total}$) measured using a quantum sensor. Data were categorized into two classes of average daily maximum temperature T: *open circles*, 6°–22°C (n = 36); *filled circles*, 22°–32°C (n = 48). The boundary (22°C) was defined as the average T of all the data points

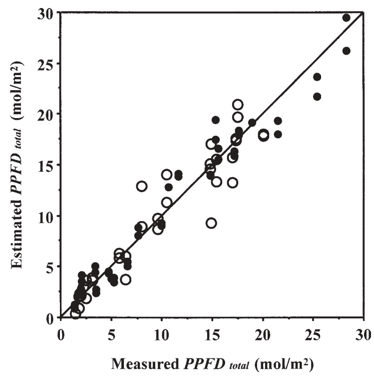

Fig. 2. The relationship of the $PPFD_{total}$ estimated using film (*yaxis*) to the $PPFD_{total}$ measured using a quantum sensor (*xaxis*). Data were categorized into two classes of T: *open circles*, 6°–22°C (n = 36); *filled circles*, 22°–32°C (n = 48). The line $y = x$ is shown for comparison

$$PPFD_{total} = (100 - F)/(1.085 + 0.051\ T) \qquad (6)$$

The regression was statistically significant ($P < 0.0001$, n = 84), with a high r^2 (0.94). Figure 2 shows the relationship between the estimated and measured $PPFD_{total}$. Because Eq. 6 includes the effect of T, the data in Fig. 2 are not segregated for the two classes of T. The errors of estimation were not significantly correlated with T ($r = 0.01$; $P = 0.91$), indicating a good correction for the effect of temperature. The errors of estimation were also not significantly correlated with $PPFD_{total}$ ($r = -0.21$; $P = 0.06$), and the absolute value of the errors averaged $1.3\,mol\,m^{-2}$ and ranged from 0.0 to $5.7\,mol\,m^{-2}$, indicating a good fit.

Discussion

In this study, we examined the applicability of color acetate film for evaluating the forest understory light environment. A good relationship between $PPFD_{total}$ and F and T was obtained from multiple-point sampling throughout the year. The relationship in Eq. 6 corrects for the effects of temperature and includes possible variation in the relationship between $PPFD_{total}$ and F across sampling points that might differ in light quality. Therefore, the method assured the broad applicability of the film, for evaluating the forest light environment, with a high accuracy of estimation. Because the regression constants will change, calibration is required for each forest.

Fukushima (1998) reported that the fading ratio of film changed irregularly until the integrated PPFD exceeded $5\,mol\,m^{-2}$. In our study, however, for low values of $PPFD_{total}$ (1.4–$5.0\,mol\,m^{-2}$), F was strongly correlated with $PPFD_{total}$ ($r = -0.75$; $P < 0.001$; $n = 28$). Therefore, there was no evidence to suggest an increased error of estimation in low-light environments.

The average of the absolute errors of estimation ($1.3\,mol\,m^{-2}$) could limit the ability of the film to accurately distinguish differences in a narrow range of light environments. However, because $PPFD_{total}$ in the understory varied by up to 20 times from 1.4 to $28.3\,mol\,m^{-2}$, the film method is well suited to ranking understory light conditions across a large number of sites. Therefore, the accuracy and low cost of color acetate film make it a good option for estimating the integrated PPFD in a forest understory.

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