Applicability of the Hemispherical Photography to Leaf Area Index Estimation in a Stand of Bamboo, *Phyllostachys pubescens*

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**ABSTRACT**

We evaluate an applicability of the hemispherical photography for estimating leaf area index (LAI) in a stand of bamboo, *Phyllostachys pubescens* Mazel ex Houz. In the *P. pubescens* stand, ten successive thinning regimes were conducted, and the repetitive hemispherical photography was performed before and after each thinning. LAI estimated from the photographs was then compared with that estimated by the allometric technique. There was a significant correlation between LAI estimated by these two methods, suggesting the applicability of the hemispherical photography. However, LAI estimated by the photographic method was significantly larger than that estimated by the allometric method. The discrepancy of the estimated LAI might be due to the bias caused by the culms and branches taken in photographs. The Monte Carlo simulation indicated that at least, but not more than, 12 hemispherical photographs per plot with 25 $m^2$ in area were necessary for stable estimation of LAI in a stand of *P. pubescens*. In conclusion, the hemispherical photography should be accepted as an effective alternative for estimating LAI in a stand of *P. pubescens*.

*Keywords*: allometric technique, hemispherical photography, leaf area index (LAI), Monte Carlo simulation

**INTRODUCTION**

Bamboo is the vernacular or common term for members of a particular taxonomic group of large woody grasses, which is widely distributed throughout the tropics, subtropics and temperate zones of the world (Scurlock et al., 2000). Lobovikov et al. (2007) estimated that there are roughly 37 million hectares of the bamboo forests in the world, which occupy 1% of the global forest area. Although the forest area has decreased in many countries, bamboo forests have progressively increased at a rate of 3% annually (Zhou et al., 2011). These facts indicate that the bamboo forests are one of the most typical types of forest in this area, and that they may strongly affect the global carbon cycling (Buckingham et al., 2011; Song et al., 2011; Lobovikov et al., 2012). Although many recent studies have focused on examining the capacity of fixing carbon in bamboo forests to assess their contributions to the global carbon cycle (e.g., Gratani et al., 2008; Yen et al., 2010; Liu et al., 2011; Wen et al., 2011; Yen and Lee, 2011; Zhou et al., 2011), there has been a debate whether the bamboo forest ecosystem is a carbon sink or source (Duking et al., 2011; Song et al., 2011; Zhou et al., 2011). The reason of this conflict will be that studies on the bamboo are remarkably scarce and little is known about the carbon cycling of the bamboo forests (Isagi, 1993; Isagi et al., 1997).

The leaf area index (LAI) is defined as the total one-sided area of photosynthetic tissue per unit ground area (Jonckheere et al., 2004). Since the leaf or canopy layer governs the carbon sequestration in a forest stand, LAI is a major determinant of the carbon cycle in forest ecosystem. Despite of its importance, the direct measurement of LAI is time-consuming and labor-intensive (Majasalmi et al., 2012), and hence it is an inapplicable method for the spatially and temporally intensive studies. A most widely used alternative measurement of LAI is the allometric technique, which relies on the allometric power relationship between leaf area and any dimension variables such as diameter at breast height (dbh) and tree height (see reviewed by Jonckheere et al., 2004). The allometric technique will be a powerful alternative for estimating the total leaf mass or LAI, if reliable and appropriate allometric equations can be obtained. As the most reliable approach, the allometric technique has often been applied to the estimation of the total foliage mass or LAI in the bamboo forests (Toyota and...
Mori, 1985; Kawahara et al., 1985, 1987; Isagi, 1993; Isagi et al., 1997; Murakami et al., 2006; Du et al., 2011). On the other hand, the remote sensing technique enables us to estimate LAI over a large area of bamboo forests (Zhang et al., 2011). This technique is however based on the empirical-statistical approach that relates ground-measured LAI to the spectral vegetation index. For this reason, it still requires the ground-truth of LAI estimated by the other direct or indirect method (Breda, 2003).

Another effective alternative for estimating LAI may be the hemispherical photography (e.g., Jonckheere et al., 2004; Zhang et al., 2005; Garrigues et al., 2008; Chianucci and Cutini, 2012). Once the photographs are taken, the tedious works for measuring the foliages in the field can be replaced by an easy estimation from the image analysis. Especially, an inexpensive digital camera that can be equipped the exclusive fish-eye lens is now available. The digital hemispherical photography should be useful in spatially and temporally intensive studies, since we can save on the cost, time and labor for film processing and image scanning (Inoue et al., 2004b). Furthermore, studies have shown the effectiveness of hemispherical photography for estimating LAI in both coniferous and broad-leaved forests (e.g., van Gardingen et al., 1999). These features make the hemispherical photography one of the most effective devices for estimating LAI. However, so far the studies on the measurement of LAI in a bamboo forest using hemispherical photography (including the other optical devices such as Plant Canopy Analyzer, LAI-2000) have been superficial (Onozawa et al., 2009; Shinohara et al., 2010; Komatsu et al., 2010; Kume et al., 2010; Zhang et al., 2011). In addition, accuracy of LAI in bamboo forests estimated by the hemispherical photographs has not validated with direct reference measurement of LAI, since LAI reported in these studies has been estimated as a supplemental information on the water cycling (Onozawa et al., 2009; Shinohara et al., 2010; Komatsu et al., 2010; Kume et al., 2010) or a ground-truth for the remote sensing (Zhang et al., 2011).

New shoots of *Phyllostachys pubescens* Mazel ex Houz., which is one of the largest bamboos in Japan, are produced in early spring at a density of 500-3000 shoots per ha, independent of the light environment within the stand (Li et al., 1998). After emergence, the shoots elongate rapidly and reach their mature heights (ca. 10-20 m: Li et al., 2000) in a matter of two or three months (Zhou et al., 2005). The branches and leaves of the new elongated culms are then expanded in the canopy layer of the old culms (Gratani et al., 2008). For these reasons, the bamboos compose the very dense stand with an extremely closed canopy (Li et al., 1999), suggesting that the canopy structure of bamboo forests would be markedly different from that of the forests composed of tree species. Therefore, it is necessary to examine whether the hemispherical photography can be applied to the estimation of LAI in bamboo forests as well as the coniferous and broad-leaved ones.

In addition, the hemispherical photographs should be taken under still and cloudy conditions (e.g., Inoue et al., 2004a, b, 2011a; Jonckheere et al., 2004; Yamamoto et al., 2010). The time and labor become intensive as the number of photographs increases. For these reasons, it is reasonable to taken the photographs as small number as possible with an appropriate precision. Sampling intensity is the key issue when performing ground measurement of LAI not only with LAI-2000 but also with hemispherical photography (Nackaerts et al., 2000; Weiss et al., 2004; Majiasalmi et al., 2012). However, it is unknown how many hemispherical photographs should be taken when estimating LAI in a bamboo stand. Answering these two questions will be useful not only for the spatially and temporally intensive studies on the carbon cycling in bamboo forests but also for the ground-truth of the remote sensing technique.

The objective of this study was thus to assess the applicability of hemispherical photography for estimating LAI in a stand of bamboo, *P. pubescens*. In this study, LAI estimated by hemispherical photography was firstly compared to that by allometric technique, and then the applicability of the hemispherical photography to the *P. pubescens* forests was discussed. Secondly, the Monte Carlo simulation was applied to derive the number of photographs required for estimating LAI in a stand of *P. pubescens*.

**MATERIALS AND METHODS**

**Study Site**

This study was conducted in a stand of *P. pubescens* in a typical suburban forest, Mt. Toshima, located in the eastern part of Kumamoto City, Kumamoto Prefecture, western Japan (32°49’N, 130°48’E; Inoue et al., 2011b, 2012). The average annual temperature and annual rainfall in Kumamoto City were 16.8°C and 2,060 mm, respectively. *P. pubescens* was distributed from the foot to the mountainside of Mt. Toshima, and the upper part of this mountain was dominated by the evergreen broad-leaved species such as *Quercus glauca* Thunb. ex Murray, *Castanopsis cuspidata* Schottky and *Symplocos lucida* Sieb. et Zucc. The study site was located on a south-facing gentle slope and the altitude ranged from 80 to 90 m. This stand was dominated by *P. pubescens* and few seedlings of tree species (e.g., *Nageia nagi* Thunb. Kuntze, *Camellia japonica* L., *Cinnamomum camphora* L. Presl, and *Osmanthus × fortunei* Carr.) were scattered at the forest floor. According to the local residents, this site was originally used for upland farming until a few decades ago, and is now being turned into a *P. pubescens* stand because of the planting of bamboo and subsequent abandonment.

**Field Inventory**

A square plot of 15 m × 15 m was established in this stand, and the plot was then divided into nine 5 m × 5 m sub-plots. The diameter at 1.2 m height above ground level (dbh) of all culms was measured, and the culm position and age were also recorded. The culm age was determined by the following criteria: (1) 1-year-old bamboo had sheaths that still remained in the culm base and the culm surface was covered with a clear white powder; (2) In 2-year-old or greater bamboo, the sheaths disappeared from the culm base, the white powder began to disappear from the culm surface gradually, and the...
culm turned light green or yellowish green in color.

In this plot, ten successive thinning regimes were performed after the elongation of the new culms and the development of leaves of P. pubescens (from October 2010 till January 2011), so that the change in LAI with culm density could be evaluated and the effect of leaf fall of P. pubescens on the LAI estimation could be ignored. The thinning culms were preferentially selected from dead, older and smaller culms, so that the thinning ratio by the number of culm for each thinning was approximately 5% (based on the initial culm density) and the residual culms were distributed as random as possible. Only three dead smaller culms with no leaves were found among 129 culms in the plot before the thinning experiment, suggesting that the effect of these dead culms on the LAI estimation would be comparatively small. General description of the experimental stand is given in Table 1. For the detail of this thinning experiment, see Inoue et al. (2012).

Estimation of Leaf Area Index

To estimate LAI in the P. pubescens stand, the repetitive hemispherical photography was performed before and after each thinning. For the photography, the center sub-plot was divided into twenty-five 1 m × 1 m quadrats. On the each corner of these quadrats, color hemispherical photographs were taken in still and overcast sky conditions using a digital cameras (Coolpix 4500, Nikon Corporation, Tokyo, Japan) with an exclusive fish-eye lens (Fish-eye converter FC-E8, Nikon Corporation, Tokyo, Japan). The camera was mounted at a height of 1.2 m above ground on a tripod and leveled with a bubble level (Inoue et al., 2004a, b, 2011a). The height of the seedlings found at the forest floor was lower than the camera height, indicating no effects of the seedlings on the estimation of LAI. The camera settings when taking photographs were as follows (Yamamoto et al., 2010): The reference exposure setting (shutter speed and lens aperture) for an open sky outside the forest was recorded using the Auto mode of the digital camera with an exclusive fisheye lens immediately before entering the forest. The photographs were then taken with the recorded reference exposure setting. The setting for the metering method of light for the digital camera was fixed using the center-weighted method. Inoue et al. (2004b) found no effects of different image quality and size of digital hemispherical photography on light environment estimates, and therefore the Normal image mode (2,272 × 1,704 pixels) was selected in this study. The resulting total number of hemispherical photographs taken in this study was 396.

The hemispherical photographs were downloaded directly from the digital camera to a personal computer (FM-V Deskpower, Fujitsu Corporation, Tokyo, Japan). An automatic thresholding algorithm based on the classification error (Kittler and Illingworth, 1986) was applied to the blue channel images (Inoue et al., 2011a). LAI was estimated from the binary images based on the algorithm proposed by Welles and Norman (1991) with the assumption of random spatial distribution of the leaves of P. pubescens (Zhang et al., 2011). The fish-eye lens used in this study was designed to produce a simple polar projection, but it did not conform exactly to this design specification (Inoue et al., 2004a). LAI was therefore estimated by calibrating the view angle and lens distortion of the fish-eye converter (Inoue et al., 2004a). These image analyses were performed using the LIA for Win32 (LIA32: Copyright K. Yamamoto) image processing program, developed by Delphi 5.0J (Inspire Corporation, Scot Valley, USA) and available freely on the Internet at http://www.agr.nagoya-u.ac.jp/~shinkan/LIA32/index-e.html.

For the comparison, LAI in the stand of P. pubescens was also estimated using the allometric power equations between leaf biomass and diameters at breast height (dbh). In this study, the following allometric equations determined in the two stands of P. pubescens in Satsuma and Aira Towns, Kagoshima Prefecture, southwestern Japan, were used to estimate leaf biomass (Murakami et al., 2006):

\[
\begin{align*}
L &= 0.0075 \times 10^{0.7205} \text{ (1-year-old culms for Satsuma)} \\
L &= 0.0198 \times 10^{1.7230} \text{ (1-year-old culms for Aira)} \\
L &= 0.0001 \times 10^{1.1725} \text{ (2-year-old or greater culms for Satsuma)} \\
L &= 0.0001 \times 10^{1.2308} \text{ (2-year-old or greater culms for Aira)}
\end{align*}
\]

where \(L\) is the leaf dry mass per culm, \(d\) is the dbh. The leaf biomass for each culm was estimated by the two equations and then averaged. Total leaf biomass in the stand was computed by summing up the estimated leaf biomass for each culm. LAI was obtained by multiplying the computed total leaf biomass by the specific leaf area observed in our site (149.2 cm² g⁻¹; Sakuta, unpublished data). The dead culms as mentioned above were excluded from the computation of LAI by the allometric technique, whereas the method using hemispherical photography is called "photographic method".

Data Analysis

LAI estimated by the photographic method, LAI(p), was compared with LAI based on the allometric method, LAI(a), using Wilcoxon sign rank test. Pearson’s correlation coefficient test and regression analysis were also performed to examine the relationship between LAI(a) and LAI(p).
To evaluate how many hemispherical photographs were required to estimate LAI appropriately, the change in LAI with the number of photographs was examined for each time (before and after each thinning) using the Monte Carlo simulation technique as follows: First, samples \( n = 2-36 \) were randomly selected from the original data pool \( n = 36 \) without replacement, and then average LAI was estimated for each number of photographs. After repeating the above procedure 10,000 times, the probability density function (PDF) of the average LAI was determined. Finally, the coefficient of variation (CV) was computed from the average and the standard deviation of the PDF, and then the change in CV with the number of photographs was analyzed. All statistical procedures were performed with the R software ver. 3.0.1 for Windows (R Development Core Team, 2013).

RESULTS

Fig. 1 compares LAI estimated by the allometric method, LAI(a), and by the photographic method, LAI(p), in the stand of \( P. \) pubescens. As the thinning progressed, LAI(a) monotonically decreased from 4.83 to 2.52 ha\(^{-1}\), whereas LAI(p) decreased from 5.34 (before thinning) to 3.08 ha\(^{-1}\) (after 10th thinning). Although there was a significantly positive correlation between LAI(a) and LAI(p) \( (r = 0.927, P < 0.001) \), Wilcoxon sign rank test indicated that LAI(p) was significantly larger than LAI(a) \( (P < 0.01) \). The relationship between LAI(a) and LAI(p) could be expressed by the following linear equation:

\[
\text{LAI}(p) = 0.852 \times \text{LAI}(a) + 0.962 \quad (r^2 = 0.874, P < 0.001).
\]

The intercept of Eq. (5) was significantly different from zero \( (P < 0.05) \), indicating that the ratio of LAI(p) to LAI(a) was not a constant.

Fig. 2 depicts the relationship between the number of hemispherical photographs and the coefficient of variation (CV) of LAI computed with the Monte Carlo simulation technique. Since the variation in LAI was the largest after 6th thinning regime, only the result at the time just after 6th thinning is given in this figure. The CV rapidly decreased with increasing number of photographs when the number of photographs was <12, whereas it was almost stable and <2% when the number of photographs was >12.

DISCUSSION

Comparison of LAI Estimated by Allometric and Photographic Methods

Comparison of LAI estimated by the two different methods indicates that LAI(p) was significantly larger than that by LAI(a) (see Fig. 1). Several studies have compared LAI estimated by hemispherical photography with the direct
measured LAI (e.g., Comeau et al., 1998; van Gardingen et al., 1999; Breda, 2003). Most of them conclude that the hemispherical photography underestimates LAI compared with the direct measurement. Jonckheere et al. (2004) summarize that the sources of error when estimating LAI using hemispherical photography are divided into the image acquisition, image analysis and violation of model assumptions. Among the sources of error, Jonckheere et al. (2004) said that the clumping of leaves seems to be the main factor causing the underestimation of LAI. By contrast, Zhang et al. (2011) argued that the assumption of random spatial distribution of the leaves is generally true for bamboo forests. For this reason, we assume the random spatial distribution of the leaves when estimating LAI from hemispherical photography, which results in the overestimation of LAI compared with the allometric method. These facts imply that the influence of the other factors on LAI estimation which produces an overestimation may be greater than the influence due to the clumping bias (Breda, 2003; Jonckheere et al., 2004).

The possible another reason of the discrepancy between LAI(a) and LAI(p) might be due to the bias caused by the culms and branches taken in photographs. As Weiss et al. (2004) indicated, the estimate from hemispherical photography is an effective leaf area index (LAIe) or plant area index (PAI) rather than LAI. To obtain not LAIe but LAI, the bias due to the contribution of culms and branches should be corrected. Chen (1996) found the relationship between LAIe and LAI as follows:

\[ \text{LAI} = (1 - a) \text{LAIe} \left( \gamma_a / \Omega_a \right) \]  

where \( a \) is the ratio of woody surface area to total surface area; \( \gamma_a \) is the shoot clumping factor; \( \Omega_a \) is the clumping index quantifying the effect of foliage clumping at larger scales than the shoot, and \( \gamma_a / \Omega_a \) is the total stand clumping index. Assuming that the foliage distribution is spatially random (Zhang et al., 2011), the term, \( \gamma_a / \Omega_a \), in Eq. (6) becomes unity (Barcley et al., 2000) and Eq. (6) can be rewritten as

\[ \text{LAIe} = \text{LAI} / (1 - a) \]  

Now suppose that LAIe and LAI in Eq. (7) are, respectively, equal to LAI(p) and LAI(a), we have

\[ \text{LAI(p)} = \text{LAI(a)} / (1 - a) \]  

By eliminating LAI(a) from Eqs. (5) and (8), the ratio of woody surface area to total surface area, \( a \), can be written as

\[ a = (0.962 / \text{LAI(p)} - 0.148) / 0.852 \]  

In this study, the observed LAI(p) ranged from 3.08 to 5.34 ha ha \(^{-1}\). Substituting these values of LAI(p) into Eq. (9) yields the estimate of the ratio \( a \) in our site, which varies from 0.038 to 0.193 with LAI(p). As shown in Eq. (5), the ratio of LAI(a) to LAI(p) in the stand of \( P. \) pubescens was not a constant. The reason of this inconstancy would be that the ratio of woody surface area to total surface area varies with culm density as suggested by Eq. (9). Gower et al. (1999) reported that the contribution of woody surface area to total surface area varies with culm density from 5 to 35%. Breda (2003) also reviewed the ratio reported in previous studies and found that the value of \( a \) ranges from 3 to 41%. The estimated ratio for the studied stand of \( P. \) pubescens (3.8 to 19.3%) falls within a reported range for the tree species (Gower et al., 1999; Breda, 2003) and into the category of lower value of \( a \). Since the stand of \( P. \) pubescens

\[ \text{Fig. 2} \quad \text{Relationship between the number of photographs and the coefficient of variation (CV) of LAI in a stand of Phyllostachys pubescens computed by the Monte Carlo simulation.} \]
bears more leaves compared to that of tree species (e.g., Isagi et al., 1997), the lower value of $a$ showed the reasonability of the result of the present study. These facts demonstrated that the hemispherical photography should be accepted as an effective alternative for estimating LAI in a stand of $P. pubescens$.

**How Many Hemispherical Photographs are Necessary When Estimating LAI?**

In the present study, 36 hemispherical photographs were taken before and after each thinning regime. However, it is preferable that LAI can be estimated from the hemispherical photographs as small number as possible. Therefore, the Monte Carlo simulation was applied to examine how many photographs are necessary when evaluating LAI in the $P. pubescens$ stand. To determine the optimal number of photographs for estimating LAI, we use -0.1% as the threshold of the change in the CV ($dCV/da$), i.e., a decrease in CV of less than 0.1% when increasing the number of photograph by one. As shown in Fig. 2, CV rapidly decreased with increasing the number of photographs when $dCV/da < -0.1\%$, whereas the CV slightly decreased with increasing the number of photographs and almost stable when $dCV/da > -0.1\%$. The minimum number of photographs with continuous $CV/da < -0.1\%$ is defined as the optimal number of photographs in the present study. With this criterion, the optimal number of photographs is estimated to be 12, and CV of LAI is less than 2%. For the photographs taken after 4-th thinning with the smallest variation in LAI, it is necessary to take only six photographs based on the same criterion. Therefore, to estimate LAI in the $P. pubescens$ stand, it would be necessary to take at least 12 hemispherical photographs per plot with 25 $m^2$ in area but not necessary more than 12 photographs.

**CONCLUSIONS**

This study evaluates an applicability of hemispherical photography for estimating LAI in the stand of $P. pubescens$. The result showed that LAI estimated by photographic method, LAI(p), is highly correlated with LAI estimated by the allometric technique, LAI(a), suggesting the applicability of the hemispherical photography. We also propose an effective sampling strategy; only 12 hemispherical photographs per plot with 25 $m^2$ in area are enough for estimating LAI in $P. pubescens$ stands. These findings will be effective in the future studies for evaluating the carbon cycling in stands of $P. pubescens$. In conclusion, the hemispherical photography should be accepted as an effective device for estimating LAI in a stand of $P. pubescens$.

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