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On improving the accuracy of digital hemispherical photography measurements of seasonal leaf area index variation in deciduous broadleaf forests

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Abstract: Optical methods have been widely used to estimate seasonal changes of the leaf area index (LAI) in forest stands because they are convenient and effective; however, their accuracy in deciduous broadleaf forests has rarely been evaluated. We estimate the seasonal changes in the LAI by combining periodic observations of leaf area variation with litter collection (LAI_{dir}) in deciduous broadleaf forests and use these estimates to evaluate the accuracy of optical LAI measurements made using digital hemispherical photography (DHP). We also propose a method to correct DHP-derived LAI (LAI_{DHP}) values for seasonal changes in major factors that influence the determination of LAI, including the woody to total area ratio (α), the element clumping index (Ω_E, using three different methods), and the photographic exposure setting (E). Before these corrections were made, LAI_{DHP} underestimates LAI_{dir} by 14%–55% from 21 May to 1 October but overestimates it by 78% on 12 May and by 226% on 11 October. Although pronounced differences are observed between LAI_{dir} and LAI_{DHP}, they are significantly correlated ($R^2 = 0.85$, RMSE = 0.32, $P < 0.001$). After considering seasonal changes in α, Ω_E, and E, the accuracy of LAI_{DHP} improves markedly, with a mean difference between the corrected LAI_{DHP} and LAI_{dir} of <17% in all periods. The results suggest that the proposed scheme for correcting LAI_{DHP} is useful and effective for estimating seasonal LAI variation in deciduous broadleaf forests.

Key words: leaf area index, leaf phenology, litter collection, digital hemispherical photography (DHP), seasonal changes.

Résumé : Des méthodes optiques ont été largement utilisées pour estimer les variations saisonnières de l'indice de surface foliaire (ISF) de peuplements forestiers en raison de leur commodité et de leur efficacité, mais leur précision dans les forêts de feuillus décidus a rarement été évaluée. Les variations saisonnières de l'ISF ont été estimées en combinant des observations périodiques de la variation de la surface foliaire à l'aide de récolte de litière (ISF_{dir}) dans des forêts de feuillus décidus et en utilisant ces estimations pour évaluer la précision des mesures optiques de l'ISF faites à partir de photographies hémisphériques digitales (PHD). Nous proposons aussi une méthode pour corriger les valeurs de l'ISF provenant de PHD (ISF_{PHD}) en utilisant les changements saisonniers dans les principaux facteurs qui influencent la détermination de l'ISF, incluant le rapport entre la surface ligneuse et la surface totale (α), l'indice d'agglomération des éléments (Ω_E, selon trois méthodes différentes) et le réglage de l'exposition photographique (E). Avant de faire ces corrections, les valeurs de l'ISF_{PHD} sous-estimaient celles de l'ISF_{dir} de 14 % à 55 % entre le 21 mai et le 1 octobre, mais les surestimaient de 78 % le 12 mai et de 226 % le 11 octobre. Bien que des différences importantes soient observées entre l'ISF_{dir} et l'ISF_{PHD}, ces variables sont significativement corrélées ($R^2 = 0,85$, EMQ = 0,32, $p < 0,001$). Après avoir pris en compte les variations saisonnières de α, Ω_E et E, la précision de l'ISF_{PHD} a augmenté considérablement; la différence moyenne entre les valeurs corrigées de l'ISF_{PHD} et de l'ISF_{dir} était inférieure à 17 % pour toutes les périodes. Ces résultats indiquent que la méthode proposée pour corriger l'ISF_{PHD} est utile et efficace pour estimer la variation saisonnière de l'ISF dans les forêts de feuillus décidus. [Traduit par la Rédaction]

Mots-clés : indice de surface foliaire, phénologie foliaire, récolte de litière, photographie hémisphérique digitale, changements saisonniers.

1. Introduction

The leaf area index (LAI), defined as half the total green leaf area per unit ground surface area (Chen and Black 1992), is a major determinant of gross primary production (GPP) (Gower et al. 1999; Barr et al. 2004; Saigusa et al. 2005; Gonsamo et al. 2013). Detailed information about seasonal LAI variability is essential for accurate modeling of net ecosystem exchange in temperate forests and other ecosystem processes (e.g., carbon uptake, leaf respiration, and photosynthesis) (Calvo-Alvarado et al. 2008; Samanta et al. 2012). Therefore, methods to increase the accuracy of seasonal LAI estimates have recently gained increasing attention (Bequet et al. 2011; Ryu et al. 2012; Potithep et al. 2013; Gonsamo and Chen 2014).

To date, several direct and indirect methods have been used to estimate the LAI in forest stands. Direct methods include harvesting, allometry, and litter collection (Gower and Norman 1991; Bréda 2003; Ryu et al. 2010; Leblanc and Fournier 2014). The harvesting method can be accurate, but it is destructive, time consuming, and practical only for small areas. Allometry is less destructive but is often limited by stand specifics such as species, season, age, density, and other attributes (Smith 1993; Chen and Cihlar 1995a; Küßner and Mosandl 2000). It also contains some uncertainty because of limited sampling (Marshall and Waring 1986; Chen 1996). Moreover, it is largely impossible to detect seasonal changes in LAI in a forest stand with either of these two methods. Litter collection is used to estimate the LAI by combining measurements of leaf litter with specific leaf area (SLA)

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(Chason et al. 1991; Fassnacht and Gower 1997). It is the only nondestructive direct method for LAI estimation and is most effective for deciduous forests. Recently, Nasahara et al. (2008) effectively estimated seasonal changes in a deciduous forest's LAI using both litter collection and in situ observations of seasonal variation in leaf area on sample live shoots. This procedure is considered to provide reliable results for the validation of indirect methods throughout the year in deciduous forests.

Indirect methods are more convenient, effective, and suitable for detecting temporal dynamics in LAI or for long-term monitoring. These methods infer LAI from measurements of radiation transmission through the canopy based on radiative transfer theories (Ross 1981). Among these indirect methods, digital hemispherical photography (DHP) and the LAI-2000 plant canopy analyzer (LI-COR Environmental, Lincoln, Nebraska) have been particularly useful for estimating LAI, because they can simultaneously measure the canopy gap fraction from several zenith angles. Recently, DHP has been increasingly used for this purpose because of advances in digital photography that provide fast, inexpensive, and permanent records of the canopy structure (Chen et al. 1997; Gonsamo and Pellikka 2009; Pueschel et al. 2012; Zhao et al. 2014).

The negatively biased LAI values arising from optical methods have usually been reported by many previous studies (e.g., Gower and Norman 1991; van Gardingen et al. 1999; Macfarlane et al. 2007; Olivas et al. 2013). Most of these studies, however, reported only observed differences in LAI between direct and indirect methods over a certain period (e.g., the annual maximum LAI period), and few studies have evaluated the accuracy of optical methods for estimating seasonal LAI variation, validated against direct methods, for a forest stand. Although optical techniques have limitations, they are particularly useful for tracking seasonal LAI variation because they are less labor intensive than the alternative direct methods of litter collection and leaf seasonality measurement. Therefore, there is interest in evaluating the reliability of optical methods for measuring seasonal LAI variation in a forest stand.

It is widely recognized that for the optical estimation of LAI, the presence of woody materials and clumping effects must be considered (Chen et al. 1997; Jonckheere et al. 2004; Mason et al. 2012) because optical methods often treat woody materials (e.g., stems and branches) as leaves and assume that leaves are randomly distributed in space. Thus, the effective LAI (L_e) is used to describe a LAI that is directly inverted from gap fraction measurements by assuming a random spatial distribution of leaves (Chen and Black 1992). However, the distribution of leaves within a forest canopy is rarely random and often clumped into distinct structures (e.g., crowns, branches, and twigs). Frequently, the influence of woody materials on optical LAI measurements in a deciduous forest is removed by measuring the woody area index (WAI) during the leafless periods and then subtracting it from the plant area index (PAI), as described in Kucharik et al. (1998) and in Eriksson et al. (2005). This method assumes that the contribution of woody materials to the PAI does not change throughout the year, although in reality, it varies seasonally. The contribution is minimal during the peak growing season because some woody materials (particularly small branches and twigs) are shadowed by leaves above the supporting branches. In the fall, the contribution becomes large because (i) the PAI decreases with leaf fall and (ii) most woody materials become visible with the loss of leaves (Eriksson et al. 2005; Zou et al. 2009). Additionally, the accuracy of LAI estimates from DHP (LAI_{DHP}) is affected by exposure errors in a closed forest stand (Chen et al. 1991; Englund et al. 2000; Song et al. 2013). When automatic exposure is used within the stand (as in the present study), the photograph is typically overexposed, causing an underrepresentation of leaves in the photo and a subsequent negative bias in L_e. In medium- and high-density canopies, L_e estimates from DHP using automatic exposure were found to be underestimated by 16%–71% relative to LAI-2000 measurements (Zhang et al. 2005). Therefore, to quickly and effectively obtain an accurate LAI_{DHP} esti-

mate (i.e., the presence of woody materials), the presence of clumping and the exposure setting must be taken into account. However, there are few reports of practical methods for correcting LAI_{DHP} to obtain accurate estimates of seasonal LAI changes in deciduous forest stands.

This study describes the use of directly measured seasonal changes in LAI, obtained from combined observations of leaf seasonality and litter fall in deciduous broadleaf forests, to validate optical measurements. The specific objectives are to (i) evaluate the accuracy of DHP for estimating seasonal changes in the LAI and (ii) propose a practical correction method for obtaining accurate LAI_{DHP} in different seasons.

2. Materials and methods

2.1. Study site

The study site is the Maoershan Ecosystem Research Station of the Northeast Forestry University (47°24′N, 127°40′E). It represents a typical deciduous forest in northeastern China, with an average altitude of 300 m above sea level and an average slope of 10°–15°. The mean annual precipitation (1989–2009) is 629 mm, of which ~50% falls between June and August. The mean annual air temperature is 3.1 °C, and the frost-free period is 120–140 days long, with early frost in September and late frost in May (Wang et al. 2013). The study was conducted using four 20m × 30 m permanent plots of mixed deciduous broadleaf plants. The forest vegetation is primarily composed of *Betula platyphylla* Sukaczev, *Fraxinus mandschurica* Rupr., *Ulmus propinqua* Koidz., *Acer mono*, and *Syringa reticulata* (Blume) H. Hara. The basic characteristics of these plots are summarized in Table 1. All of the observations were carried out from 1 May to 21 October 2012. In the study area, the leaf-out season is from May to mid-July, and the leaf-fall season is from August to October.

2.2. Measurements of SLA

The SLA was defined as the total leaf area (LA) per unit of dry mass. We monitored the SLA of major species in each plot in August, September, and October of 2012. Flat leaves in the litter traps were randomly selected, and leaves that were not flat were first flattened by spraying the litter with water. The area of each flat leaf was measured with an image scanner (model 5560; BenQ Corporation, China) at 300 dpi resolution. After measuring the LA, the samples were dried at 65 °C for 48 h to a constant mass, which was measured to the nearest milligram. The SLA for the major species in each plot was obtained by dividing the dry mass by the LA. Potential change in the SLA during leaf fall was estimated to be insignificant.

2.3. Direct estimation of the LAI (LAI_{dir})

2.3.1. Annual maximum LAI (LAI_{max})

Five litter traps were installed at random locations within each plot. Each trap had a square aperture of 1 m² and a base that was approximately 0.5 m above the ground. Leaf litter was collected on 1 and 15 August, 1, 11, and 21 September, and 1, 11, and 21 October 2012. For each deciduous broadleaf species, LAI_{max} was estimated by measuring the litter mass of the whole leaf-fall season, converting it to LA using the measured SLA for each species, and dividing the total LA by the area of the litter trap. We estimated the $LAI_{max-total}$ in a plot by adding the component LAI values of all species.

2.3.2. The seasonal changes of LAI during leaf-out seasons

Periodic in situ observations of sample shoots on 1, 12, 21, and 28 May, 4, 12, and 22 June, 5 and 15 July, and 1 August 2012 were made to investigate LA seasonality. Fifteen sample shoots from 15 individuals of five species were selected (three trees per species). For each period, we measured the size (length and width) of each leaf on the sample shoot. Generally, the leaf shape is irregular, so the area of a single leaf cannot be accurately calculated by

Table 1. General characteristics and species composition of the forest plots under investigation.

Forest plots	Major species	Density (trees·ha^{-1})	Mean DBH (cm)	Basal area (m^2·ha^{-1})
P1	*Ulmus japonica* and *Fraxinus mandschurica*	1840	7.73	19.59
P2	*Betula platyphylla* and *Ulmus japonica*	2140	8.01	19.64
P3	*Betula platyphylla* and *Acer mono*	5067	6.29	23.25
P4	*Fraxinus mandschurica* and *Ulmus japonica*	2167	9.09	35.94

Note: DBH, diameter at breast height (1.3 m).

multiplying the length by the width. Thus, to calculate the LA of a single leaf (LA$_{sin}$), a constrained linear regression was established:

$$(1) \quad \text{LA}_{\text{sin}} = cLD$$

where c is the adjustment coefficient for LA, L is the length of a single leaf, and D is the width of a single leaf. To obtain the values of c for each species, 90 mature leaves were collected from each species in July, and each sample leaf was measured for maximum length and width. Then, the area of each sample leaf was measured by scanning, and eq. 1 was rearranged to solve for c. We can also estimate the total LA of a shoot at period t (LA$_{total}(t)$) for each species:

$$(2) \quad \text{LA}_{\text{total}}(t) = \sum_{i=1}^{n} L_i(t)D_i(t)c$$

where $L_i(t)$ is the leaf length of leaf i at period t, and $D_i(t)$ is the leaf width of leaf i at period t. In this study, it is difficult to measure c values for major species in the early leaf-out season, because, at that time, leaves are small and not flat. Thus, we measured the c value for most species in both May and July, except for *F. mandschurica*, which was measured in both June (because it produced new leaves in late May) and July. However, we found that the difference of c values between two periods was <3.5% for each major species. In addition, we replaced the c value measured in July with the mean c value in both two periods in estimating LAI, and the error caused by the constant c value to final LAI was <1%. Therefore, we assumed that the c values do not change during each leaf-out season in this study. The increased ratio for the LA$_{total}$ of a shoot at period t ($R(t)$) for each species is calculated from

$$(3) \quad R(t) = \frac{\text{LA}_{\text{total}}(t)}{\text{LA}_{\text{max-total}}}$$

where LA$_{total}(t)$ is defined in eq. 2, and LA$_{max-total}$ is the annual maximum total LA of a shoot. These R data were used to represent the seasonality of LAI during the leaf-out season, and the average seasonality of the five species was assumed to represent the seasonality of the remaining unmeasured species. Thus, the seasonal changes of LAI at leaf-out period t (LAI(t)) for each plot are obtained:

$$(4) \quad \text{LAI}(t) = \sum_{i=1}^{n} \text{LAI}_{i-\text{max}}R_i(t)$$

where LAI$_{i-max}$ is the annual maximum LAI of species i, and $R_i(t)$ is the increased ratio of species i at period t.

2.3.3. The seasonal changes of LAI during leaf-fall seasons

Based on LAI$_{max-total}$, we calculated the seasonal changes of LAI during leaf-fall seasons by subtracting the decrease in LAI from the total litter of all species during each leaf-fall season. Finally, LAI for each plot was derived from the initial leaf-out date to the final leaf-fall date. In this study, the LAI derived from this direct method was defined as LAI$_{dir}$.

2.4. Indirect estimation of the LAI to obtain LAI$_{DHP}$

DHP data were acquired with a WinSCANOPY 2006 canopy analyzer (Nikon Coolpix 4500 digital camera with a 180° fisheye lens) on the same dates as the LA observations and litter collection periods. The photographs were taken at 1.3 m above the ground, with the camera mounted on a tripod, and the sample points were located near the litter traps. The photographs were obtained near sunrise (or sunset) under uniform sky conditions, with automatic exposure. A total of 85 digital hemispheric photographs were obtained at each plot for all study periods. The photographs were processed within zenith angle ranges of 30°–60°, using DHP software to derive L_e from the canopy gap fraction (Leblanc et al. 2005; Chen et al. 2006).

2.5. Correction of optical LAI estimates

Based on theory and empirical data, three corrections to the L_e (Chen 1996) yield the following accurate optical estimate of the LAI:

$$(5) \quad \text{LAI}_{\text{DHP}} = (1 - \alpha)L_e \frac{\gamma_E}{\Omega_E}$$

where α is the woody to total area ratio; Ω_E is the clumping index, quantifying the effect of foliage clumping at a scale larger than at the shoot level; and γ_E is the needle to shoot area ratio, quantifying the effect of foliage clumping at the shoot level. For deciduous broadleaf species, individual leaves are traditionally considered as foliage elements, with $\gamma_E = 1.0$. In a deciduous broadleaf forest, α is defined as WAI/PAI. The PAI depends on L_e/Ω_E (Chen 1996), defined by Chen and Black (1992) as LAI with the contribution of woody materials, so Ω_EWAI/L_e can substitute for α. Then, substitutions for α and γ_E in eq. 5 yield the following equation, as described by Leblanc and Chen (2001):

$$(6) \quad \text{LAI}_{\text{DHP}} = \frac{L_e}{\Omega_E} - \text{WAI}$$

Prior to applying eq. 6 in each study period, to improve the accuracy of LAI$_{DHP}$ estimates, the May–October vegetation period was divided into four phenological phases based on the timing of the leaf-out and leaf-fall dates for all species. Following Tillack et al. (2014), they are (*i*) early leaf-out period (ELO), (*ii*) gradient period (GP), which includes two periods, one of leaf flushing to annual maximum LAI and, following a stable LAI interval, another of subsequent continuous decrease in LAI prior to rapid leaf fall, (*iii*) stable LA period (SP), including stable periods of LAI$_{max}$ with little decrease in LAI, and (*iv*) late leaf fall (LLF), which is the period from rapid leaf fall until all the leaves have fallen. In the present study, the ELO is 12 May. The GP represents the periods from 21 May to 4 June and from 21 September to 1 October. The SP applies to the period between 12 June and 11 September, and the LLF only applies to 11 October. Both 1 May and 21 October were excluded, because there were no leaves at these times. The follow-

ing four schemes were applied to obtain accurate estimates of seasonal changes in LAI$_{DHP}$.

2.5.1. Scheme A

Noncorrected estimates of LAI, setting LAI$_{DHP}$ = L_e to compare with results from the other three schemes.

2.5.2. Scheme B

Error due to the contribution of woody materials and clumping effects in canopies was corrected using eq. 6. The contribution of woody materials (i.e., WAI) was measured during the leafless periods (1 May and 21 October) by the DHP method. Assuming that this contribution did not change during the leafy period, the WAI was subtracted directly from the PAI to remove the influence of woody materials in all study periods (i.e., ELO, GP, SP, and LLF). The mean value of WAI on 1 May and 21 October was used throughout the leafy period, i.e., regardless of the seasonal variations in the WAI contributions to LAI estimation.

The contribution of the clumping index (for easier notation, CI is used instead of Ω_E) was obtained by three different methods.

2.5.2.1. CI from gap size distribution (CI$_{CC}$)

CI$_{CC}$ is computed based on the gap size and fraction analysis (Chen and Cihlar 1995b; Leblanc 2002):

$$(7) \qquad CI_{CC} = \frac{\ln[F_m(0,\theta)]}{\ln[F_{mr}(0,\theta)]} \frac{[1 - F_{mr}(0,\theta)]}{[1 - F_m(0,\theta)]}$$

where $F_m(0,\theta)$ is the measured accumulated gap fraction greater than zero, and $F_{mr}(0,\theta)$ is the gap fraction for the canopy when large gaps that are not theoretically possible in a random canopy are removed for a given LAI and foliage element width.

2.5.2.2. CI from logarithmic gap averaging method (CI$_{LX}$)

CI$_{LX}$ is computed using a logarithmic gap averaging method (Lang and Xiang 1986) as follows:

$$(8) \qquad CI_{LX} = \frac{\ln[\overline{P(\theta)}]}{\overline{\ln[P(\theta,\varphi)]}}$$

where $\overline{P(\theta)}$ is the mean canopy gap fraction at zenith angle θ, and $\overline{\ln[P(\theta,\varphi)]}$ is the mean value of logarithmic gap fractions at zenith angle θ, separated by segments or ranges of the azimuthal angle φ. The CI value determined using this method is highly sensitive to the choice of the segment size. In theory (Lang and Xiang 1986), the physical length of the segments should ideally be 10 times the mean width of a foliage element. To determine this length on a hemispherical photograph, we need to know not only the zenith angle at which the CI is calculated, but also the mean canopy height and leaf size. For example, for a canopy with a height of 15 m and a mean leaf size of 0.05 m, the length of a photographic circle at a zenith angle of 45° is 133 m. Because the ideal averaging length is 0.5 m, the circle should be divided into 266 segments for the calculation of the mean CI. However, many of these segments would be completely shadowed by tree trunks and foliage clumps and would have no gaps. These black segments, i.e., with no gaps, produce unrealistic results, with infinitely large LAI values and CI values of zero. To address this issue, van Gardingen et al. (1999) proposed a method to add a gap of one pixel to black segments. Similarly, Leblanc et al. (2005) added a gap of one-half pixel to black segments in the implementation of Land and Xiang's method in the DHP software (used in our study). In DHP, the mean size of the foliage elements (shoots in conifer trees and leafs for broadleaf trees) in terms of the azimuthal angle range at a given zenith angle is automatically determined through an iteration procedure (Leblanc et al. 2005), and the size of the segments in terms of the azimuthal angle range is then taken as 10 times the

azimuthal angle range, corresponding to the foliage element size. Although there is a physical basis for determining the segment size, the element size determined this way is often unrealistically large, because many small gaps are not resolved in the photograph, and therefore, the segment size is also too large. Even so, there are still many black segments that require insertions of artificial gaps. Although this could be the most advanced way of implementing Land and Xiang's method on hemispherical photographs, the choice of adding a gap to black segments is arbitrary, and therefore, the results from this method are only given for comparison purposes.

2.5.2.3. CI from a combination of gap size distribution and logarithmic gap averaging method (CI$_{CLX}$)

CI$_{CLX}$ is calculated based on a combination of the concepts used in CI$_{CC}$ and CI$_{LX}$ to address problems related to both the segment size in the logarithmic gap averaging method (when large gaps are statistically unevenly distributed) and the within-segment heterogeneity in the gap size distribution method (Leblanc et al. 2005)

$$(9) \qquad CI_{CLX} = \frac{n\ln[\overline{P(\theta)}]}{\sum_{k=1}^{n} \ln[P_k(\theta,\varphi)]/CI_{CCk}(\theta,\varphi)}$$

where CI$_{CCk}(\theta,\varphi)$ is the element CI of segment k using the CI$_{CC}$ method, and $P_k(\theta,\varphi)$ is the gap fraction of segment k. The CI$_{CLX}$ is computed over n segments and integrated over the zenith angle ranges considered. This method has the same issues in determining the segment size and in treating black segments.

Smaller zenith angles result in shorter segments, which may produce erroneous results from the LX (i.e., gap size distribution) and CLX (combination of gap size distribution and logarithmic gap averaging) methods. In contrast, the segments at large zenith angles yield high proportions of mixed pixels due to light scattering and coarse image resolution. Therefore, angles ranging from 30° to 60° were used to measure LAI, because this range is the central portion of the photos between the zenith and the horizon, thus providing an approximate estimate of the entire field of view (Leblanc and Chen 2001; Gonsamo and Pellikka 2009). The three CI (i.e., CC, LX, and CLX) values were obtained by using the DHP-TRAC software, and seasonal changes were considered during all study periods. Hereafter, the clumping effects were corrected using the CC, LX, and CLX methods, and LAI$_{DHP}$ values were defined as LAI$_{DHP-CC}$, LAI$_{DHP-LX}$, and LAI$_{DHP-CLX}$, respectively. Generally, both the woody materials and clumping effects were considered in scheme B, regardless of the seasonal variations in the WAI contributions to LAI.

2.5.3. Scheme C

The contributions of woody materials and clumping effects were corrected in the same way as in scheme B. In addition, all digital hemispherical photographs were taken with automatic exposure, causing considerable underestimation of the L_e. The underestimates were corrected according to a relationship between DHP-derived L_e obtained with automatic exposure and LAI-2000 derived L_e reported by Zhang et al. (2005), regardless of the seasonal variations in the contributions of the automatic exposure to LAI estimation.

2.5.4. Scheme D

Generally, the seasonal changes of the WAI, clumping effects, and automatic exposure to LAI estimation were all considered in scheme D. The woody materials consist of stems and branches, so the WAI is the sum of the stem area index (SAI) and the branch area index (BAI). The WAI on both 1 May and 21 October was measured as in scheme B, but image software (Adobe Photoshop CS6, Adobe Systems Inc., North America) was used to extract the SAI from the WAI. First, the WAI of the digital hemispherical

photos from 1 May and 21 October was obtained using the DHP software. Second, a clone stamp tool in the image software was used to replace the branches with sky, leaving only stems on the photos. Third, the SAI was obtained by reprocessing the photos. Finally, the BAI was derived by subtracting the SAI from the WAI. The contribution of branches to LAI decreases with season and reaches its smallest value near the peak growing season, i.e., during the SP. In contrast, the contribution of stems to the LAI varies little with the season. Therefore, the contribution of branches to the LAI was ignored for the SP, but the contribution of stems to the LAI was considered throughout all study periods. This is to say that the WAI in eq. 6 represented the contribution of stems and branches during the ELO, GP, and LLF but only represented the contribution of stems during the SP, i.e., the seasonal changes of the contributions of woody materials to LAI estimation.

The correction of clumping effects was conducted as in schemes B and C. The correction of exposure in ELO and LLF was not considered, because the exposure error was <3% during these periods, which suggests that the woody materials are insensitive to the exposure setting when DHP is used to estimate LAI; however, the correction for other periods was conducted as in scheme C.

3. Results

3.1. Adjustment coefficient for LA
Significant linear correlations ($P < 0.01$) are observed between LA and the product of leaf length and width for five major species (Table 2), with the smallest R^2 value being 0.93. The largest c value is 0.69 for $S.$ $reticulate$, with $A.$ $mono$ having the smallest value of $c = 0.52$ because of its palm-shaped leaf.

3.2. LA seasonality
Seasonal changes in LA vary with species (Fig. 1). All species produce new leaves in early May, except for $F.$ $mandschurica$, which produces new leaves in late May. Rapid growth of leaves begins for $A.$ $mono$ in mid-May, with approximately 91% of LA_{total} produced by 21 May. For $S.$ $reticulate$, >94% of LA_{total} was produced by late May. In early July, $F.$ $mandschurica$ and $U.$ $propinqua$ have produced 99% and 98% of their total LAs, respectively. In contrast to these four species, the leaves of $B.$ $platyphylla$ begin to fall in late July, with the areas of fallen leaves accounting for a 25% reduction of LA_{total} by early August.

3.3. The LAI across all seasons
The mean LAI for each species is measured across all seasons by combining the LA seasonality data with the litter trap data for the four forest plots (Fig. 2). All species reach the LAI_{max} in mid-July except for $A.$ $mono$, which reaches it in mid-June. $Betula$ $platyphylla$ has the largest peak LAI, with a value of 1.81, followed by $U.$ $propinqua$, with a peak LAI value of 1.66. The life-span of $F.$ $mandschurica$ is much shorter than that of the other four species, and leaf fall is largely complete by early October.

3.4. Seasonal changes in the CI
Although the seasonal variations of CI_{CC}, CI_{LX}, and CI_{CLX} show different patterns (Fig. 3), not all of them are significant, with coefficient of variations of 4%, 2%, and 4%, respectively. Generally, the mean CI_{CC} is larger than CI_{LX} and CI_{CLX}, with values of 0.93, 089, and 0.76, respectively. The CC method utilizing the canopy information to derive the gap size distribution is based on a sound physical principle and free of subjective parameters. However, its application to photographs often suffers from the issue of insufficient photographic resolution that loses many small gaps, resulting in the underestimation of the clumping effect (i.e., the CI was too large). The LX and CLX methods can fix this problem by introducing mean length as a free parameter, which can often be adjusted to fit observations. However, these two methods suffer from issues with the determination of mean segment size and the treatment of black segments, as outlined in section 2.5.

Table 2. Constrained regression models for major species.

Species	c	R^2	P value
Betula platyphylla	0.67	0.97	<0.01
Ulmus propinqua	0.62	0.98	<0.01
Fraxinus mandschurica	0.66	0.99	<0.01
Acer mono	0.52	0.93	<0.01
Syringa reticulate	0.69	0.98	<0.01

Note: c is the adjustment coefficient. $n = 90$.

3.5. SAI measurements for the leafless periods
The SAI on 1 May in the four forest plots ranges from 0.05 to 0.17 (Table 3), with a mean value of 0.13. On average, the stems account for 19% of the total WAI at that time. The SAI on 21 October does not differ significantly than the SAI on 1 May, with a mean value of 0.14, and stems accounting for 22% of the total WAI. The SAI values are 0.10, 0.13, 0.10, and 0.24 for P1, P2, P3, and P4, respectively.

3.6. Comparison of LAI_{dir} and LAI_{DHP}
LAI_{dir} and LAI_{DHP} from uncorrected L_e (i.e., scheme A) both present robust seasonal changes in the four forest plots, with the smallest coefficients of variation being 64% and 40%, respectively (Table 4). On average, L_e underestimates LAI_{dir} by 14%–55% between 21 May and 1 October for the four plots, with the underestimation increasing with the number of leaves in the canopies. In contrast, L_e overestimates LAI_{dir} by an average of 78% and 226% on 12 May and 11 October, respectively, mainly because of the influence of woody materials on LAI_{DHP}. From 1 May to 21 October, L_e ranges from 0.68 to 2.72 for P1, from 0.55 to 2.49 for P2, from 0.64 to 3.11 for P3, and from 0.67 to 2.94 for P4. The LAI_{dir} peaks in mid-July for all four plots, with values of 6.17 ± 1.03, 5.28 ± 0.57, 6.97 ± 0.21, and 5.81 ± 0.27 for P1, P2, P3, and P4, respectively.

A significant correlation ($P < 0.001$) between LAI_{dir} and LAI_{DHP} from scheme A is observed, with $R^2 = 0.85$ and RMSE = 0.32 (Fig. 4; Table 5). However, L_e is greater than LAI_{dir} in the ELO and the LLF. In the GP, LAI_{DHP} underestimates LAI_{dir} at more than four of five sample points by 25%, on average. The mean underestimation of LAI_{dir} by LAI_{DHP} in the SP is 50%.

Generally, the accuracy of LAI_{DHP} for the ELO and LLF is improved after the scheme B correction for the WAI and CI (CC, LX, and CLX) within canopies (Fig. 5). However, the difference between LAI_{dir} and LAI_{DHP} increases in the GP, and LAI_{DHP-CC} underestimates LAI_{dir} by an average of 48%, whereas the mean underestimations were 42% and 30% for LAI_{DHP-LX} and $LAI_{DHP-CLX}$, respectively. This is likely because the contribution of woody materials is overestimated during the GP period. A significant correlation ($P < 0.001$) between LAI_{dir} and each LAI_{DHP} from scheme B is found, with minimum $R^2 = 0.85$ for $LAI_{DHP-CLX}$ and maximum RMSE = 0.52 for $LAI_{DHP-CLX}$ (Table 5). The LAI_{DHP} from scheme B still underestimates LAI_{dir} in all periods, with mean values of 50%, 49%, and 34% for LAI_{DHP-CC}, LAI_{DHP-LX}, and $LAI_{DHP-CLX}$, respectively, indicating that the error introduced from woody materials and foliage clumping is insufficient to explain the difference between LAI_{dir} and LAI_{DHP}.

A significant correlation ($P < 0.001$) between LAI_{dir} and LAI_{DHP} is found after correcting for the WAI, CI, and exposure setting, according to scheme C (Fig. 5; Table 5). Generally, the accuracy of LAI_{DHP} in scheme C is greatly improved relative to scheme B in the SP, and the average difference between LAI_{dir} and LAI_{DHP-CC} is 21% in the SP, and the average differences for LAI_{DHP-LX} and $LAI_{DHP-CLX}$ in the SP are 18% and 6%, respectively. However, in contrast to scheme B, the difference between LAI_{dir} and each LAI_{DHP} (i.e., LAI_{DHP-CC}, LAI_{DHP-LX}, and $LAI_{DHP-CLX}$) under scheme C significantly increases in the ELO and the LLF, indicating that it is not appropriate to use it for periods with few leaves.

In contrast, the accuracy of LAI_{DHP} using scheme D, with its consideration of seasonal changes of WAI, CI, and E, is improved considerably in all periods (Fig. 5; Table 5). For the ELO, the CC

Fig. 1. The seasonality of total leaf area of shoots for major species, normalized to an annual maximum of 1.0. Error bars represent the standard deviation.

method is more effective for correcting clumping effects with scheme D than the LX and CLX methods, and LAI_{DHP-CC} underestimates LAI_{dir} by 9%. For the GP, the differences between LAI_{dir} and LAI_{DHP-CC} and between LAI_{dir} and LAI_{DHP-LX} are both 6%, which is smaller than the difference between LAI_{dir} and $LAI_{DHP-CLX}$ (12%). For the SP and LLF, the CLX method is more effective than the CC and LX methods for correcting clumping effects with scheme D, and the differences between LAI_{dir} and $LAI_{DHP-CLX}$ are 5% and 17%, respectively. Generally, during the whole periods, the mean difference between LAI_{dir} and $LAI_{DHP-CLX}$ is smaller than those of LAI_{DHP-CC} and LAI_{DHP-LX}, with values of 4%, 7%, and 17%, respectively, indicating that the accuracy of seasonal LAI changes, determined by optical methods, in deciduous forests is >83% with appropriate corrections.

4. Discussion

Other than destructive sampling methods, one of the most reliable methods for estimating the LAI is to collect leaves in litter traps, especially in deciduous forests. To improve the accuracy of the litter collection method for estimating LAI, the SLA must be precisely measured because it is the greatest source of uncertainty in this method (Jurik et al. 1985). Also, SLA varies with species and season (Nouvellon et al. 2010; Ishihara and Hiura 2011; Majasalmi et al. 2013), so the SLA of major species in the four forest plots was measured here, taking into account seasonal variation in the leaf-fall season. Moreover, the species-specific SLA for each forest plot was used to estimate the LAI so as to avoid the error caused by spatial variation in SLA. Recently, it was recommended that observations of LA seasonality in leaf-out seasons be combined with litter collection data in leaf-fall seasons to estimate seasonal changes of LAI in deciduous forest stands (Nasahara et al. 2008; Potithep et al. 2013), as was done in this study. In addition, the five species that we selected for the LA seasonality observations accounted for 86% of $LAI_{max-total}$ estimated from litter collection. This means that the seasonality of approximately 14% of $LAI_{max-total}$ was uncertain. However, based on the variability among the five measured species, we estimated that the error due to this small unmeasured portion is <0.4. However, the proposed method is laborious relative to optical methods, particularly the collection and sorting of the fallen litter. Therefore, it is important to evaluate the accuracy of optical methods in this regard and to address the urgent need for a scheme to obtain accurate optical LAI estimates.

There are several reports that the DHP method produced lower LAI values than direct methods. For example, in a canopy of *Gliricidia sepium* (Jacq.) Kunth in Mexico, van Gardingen et al. (1999) found that the LAI_{DHP} based on uncorrected L_e underestimated the LAI by 50% compared with the harvesting method. Similarly, Olivas et al. (2013) reported that the DHP method underestimated LAI_{dir} by 30% in a tropical rain forest. In this study, uncorrected LAI_{DHP} underestimates LAI_{dir} by 34%–55% at similar times (e.g., June and July). However, the difference between LAI_{dir} and LAI_{DHP} varies strongly with season (on average, from −226% to 55%). The more leaves there are in the canopy, the greater is the difference, probably because (*i*) woody materials such as trunks and branches can be masked by emerged leaves, thus reducing the estimated contribution of woody materials to light interception, and (*ii*) the extent of leaf clumping within canopies increases with leaf growth. This suggests that evaluations of the accuracy of DHP for LAI measurement in different seasons are necessary.

Woody materials and clumping effects have often been reported as the main sources of error in optical LAI estimation. In this study, the WAI ranges from 0.55 to 0.74. Similar results have been reported by Dufrêne and Bréda (1995), who reported a WAI of
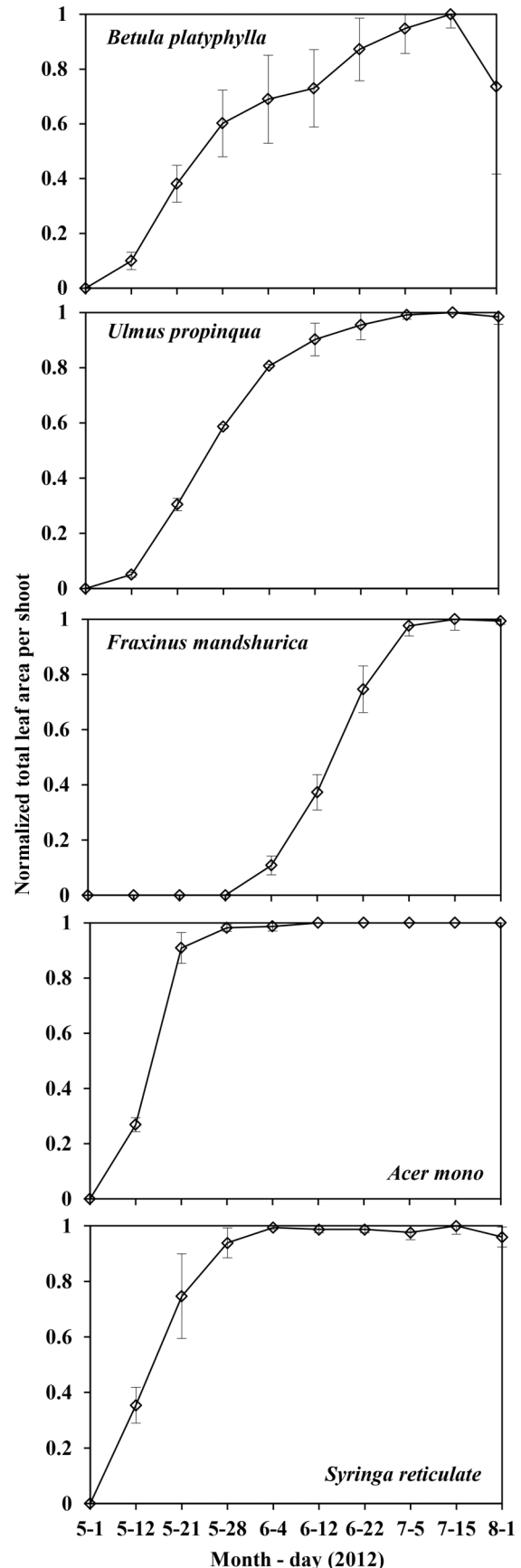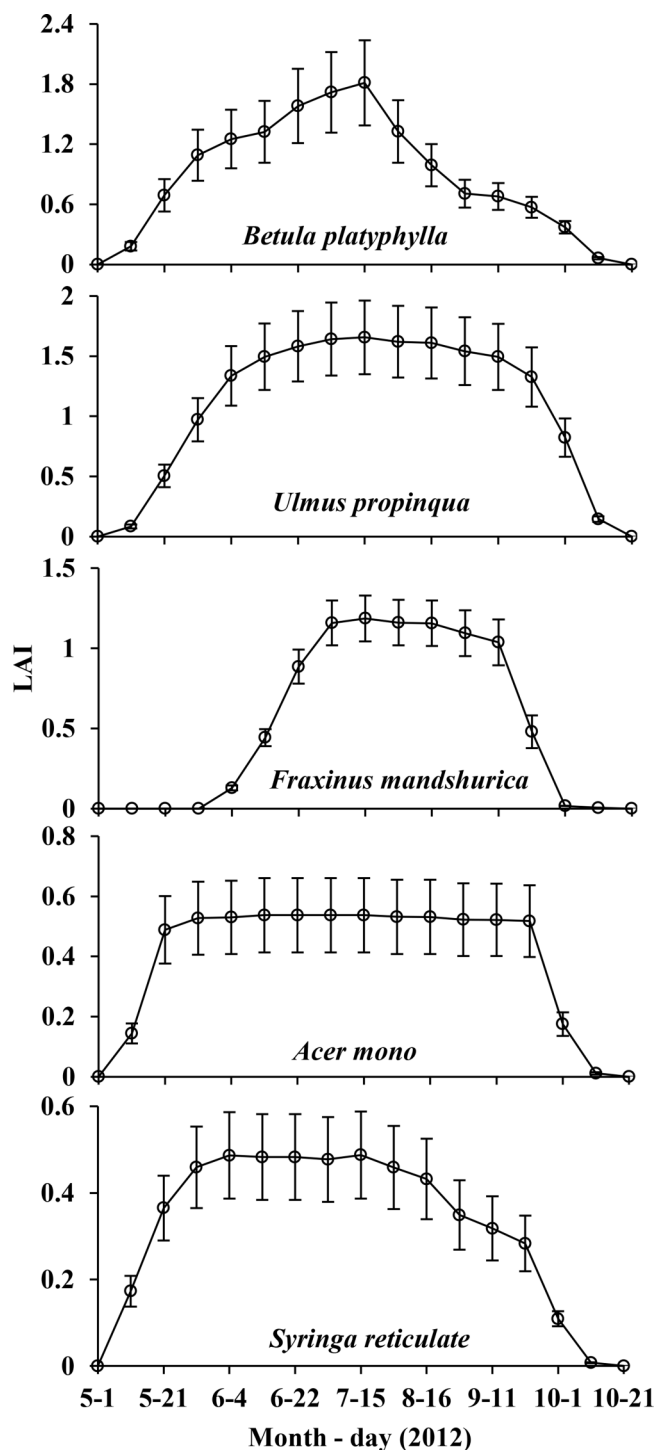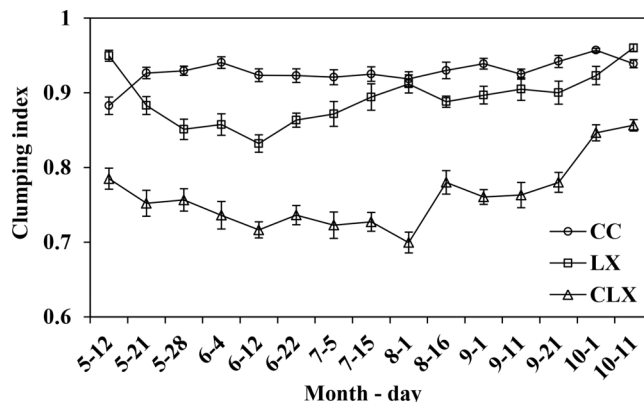
Fig. 2. The leaf area index (LAI) of species estimated by combining the leaf seasonality data (up until 15 July) with the litter trap data (after 1 August), averaged over the four plots. Error bars represent the standard deviation.

Fig. 3. Seasonal changes in the element clumping index by CC, LX, and CLX methods in the four forest plots. Values were obtained directly from the DHP-TRAC software.

after correcting for the WAI and CI (scheme B), indicating that the error introduced by these two factors cannot explain the difference between LAI_{DHP} and LAI_{dir}. Nevertheless, the LAI_{DHP} accuracy improves markedly after also considering the automatic exposure setting (scheme C), particularly in the GP and SP. These results demonstrate that the exposure setting introduces the largest uncertainty in LAI_{DHP} estimates. Chen et al. (2006) reported that LAI_{DHP} with automatic exposure underestimated LAI by approximately 40% relative to the LAI-2000. In contrast, the contributions of WAI and CI to optical LAI measurements can often cancel each other. Also, Eriksson et al. (2005) reported that optical L_e values from the LAI-2000 alone may be reliable LAI estimators in deciduous stands in the maximum LAI period.

Although the accuracy of the corrected LAI_{DHP} is improved under scheme C, the corrected LAI_{DHP} overestimates LAI_{dir} by >99% in the ELO and by 170% in the LLF. This likely reflects the greater contribution of woody material than leaves to the LAI_{DHP}, because the WAI accounts for >90% of the total L_e in these two periods, and there is nearly no influence of automatic exposure setting on the estimation of the LAI in periods with few leaves. For example, the difference between automatic exposure and correct exposure LAI_{DHP} values (e.g., Zhang et al. 2005) on 1 May and 21 October is <3%, likely because even with automatic exposure, the contrast between the woody materials and the sky was sufficiently large for DHP to differentiate. Therefore, correcting LAI_{DHP} for automatic exposure in periods with few leaves may add significant error to the estimates. In SP periods, the difference between LAI_{dir} and LAI_{DHP-CC} with scheme C is still 21%, likely due to the overestimation of the contribution of woody materials.

Several studies have observed seasonal variations in the contribution of woody materials to LAI_{DHP} (e.g., Dufrêne and Bréda 1995; Eriksson et al. 2005; Jonckheere et al. 2005; Kalácska et al. 2005; Zou et al. 2009), because the expanded leaves mask some of the woody material, particularly the branches. Additionally, Kucharik et al. (1998) reported that branches generally intercept insignificant amounts of beam radiation in boreal forests and, therefore, do not significantly bias indirect LAI measurements, but stems may not be similarly shaded by leaves. Also, Dufrêne and Bréda (1995) reported that only stems accounted for the WAI during the leaf-out period (SP in this study), and their erect position results in only minimal radiation interception. Previous researchers have also recommended that seasonal changes in the contribution of woody materials be considered in LAI_{DHP} corrections (e.g., Barclay et al. 2000; Zou et al. 2009). In this study, branch area, as quantified by the BAI, accounts for 81% and 78% of the total WAI on 1 May and 21 October, respectively, a result in agreement with previous studies. For example, Whittaker and Woodwell (1967) reported

0.67 in a *Quercus petraea* (Matt.) Liebl. stand, and by Cutini et al. (1998), who reported a WAI of 0.80 in a deciduous broadleaf forest stand. During the whole periods, the CI_{CC} ranges from 0.88 to 0.95, and similar CI values (from 0.89 to 0.96) were reported by Chen et al. (2006) in deciduous forests. In addition, correcting for CI resulted in higher LAI values than correcting for the L_e values alone, whereas correcting for the WAI resulted in lower LAI values. Generally, the accuracy of the LAI_{DHP} does not improve significantly

Table 3. The stem area index (SAI) during the leafless periods, 1 May and 21 October, in each of the four forest plots, as well as the mean of all four plots.
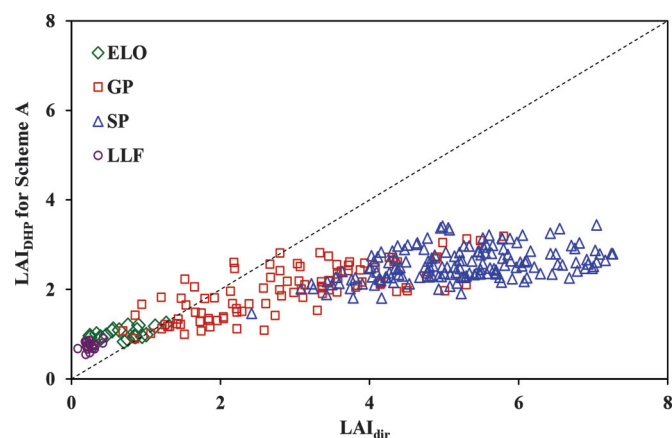
	P1		P2		P3		P4		Mean	
Month-day	SAI	SAI/WAI (%)	SAI	SAI/WAI (%)	SAI	SAI/WAI (%)	SAI	SAI/WAI (%)	SAI	SAI/WAI (%)
5-1	0.10	14	0.05	8	0.19	29	0.17	24	0.13a	19
10-21	0.10	15	0.13	24	0.10	13	0.24	36	0.14a	22

Note: Identical lowercase letters in the same column indicate that there is no significant difference ($P < 0.05$) between different periods. WAI, woody area index.

Table 4. Direct and indirect estimates (LAI_{dir} and L_e, respectively) of seasonal changes in the LAI in the four forest plots, as well as the mean of all four plots.

	P1			P2			P3			P4			Mean
Date (month-year)	LAI_{dir}	L_e	Dif. (%)	LAI_{dir}	L_e	Dif. (%)	LAI_{dir}	L_e	Dif. (%)	LAI_{dir}	L_e	Dif. (%)	Dif. (%)
5-1	0	0.68 (0.10)	—	0	0.58 (0.11)	—	0	0.64 (0.08)	—	0	0.72 (0.14)	—	—
5-12	0.46 (0.13)	1.00 (0.08)	−126	0.49 (0.24)	0.98 (0.14)	−148	1.01 (0.20)	1.10 (0.15)	−10	0.82 (0.15)	1.01 (0.09)	−28	−78
5-21	1.97 (0.34)	1.53 (0.15)	20	1.69 (0.77)	1.61 (0.15)	−15	3.32 (0.57)	2.37 (0.14)	27	2.06 (0.24)	1.59 (0.24)	22	14
5-28	3.17 (0.41)	2.40 (0.26)	23	2.49 (1.06)	2.06 (0.19)	2	4.53 (0.62)	2.82 (0.24)	37	2.91 (0.29)	2.31 (0.36)	20	21
6-4	4.19 (0.48)	2.40 (0.26)	42	3.11 (1.12)	2.35 (0.25)	15	5.09 (0.56)	2.86 (0.26)	44	3.61 (0.34)	2.30 (0.36)	36	34
6-12	4.93 (0.58)	2.39 (0.21)	51	3.72 (0.94)	2.27 (0.21)	39	5.47 (0.43)	2.36 (0.27)	56	4.30 (0.31)	2.63 (0.24)	38	46
6-22	5.65 (0.83)	2.65 (0.27)	52	4.61 (0.70)	2.20 (0.18)	51	6.29 (0.28)	2.98 (0.26)	53	5.17 (0.26)	2.68 (0.19)	48	51
7-5	6.10 (1.01)	2.71 (0.23)	54	5.14 (0.56)	2.47 (0.44)	52	6.74 (0.23)	2.68 (0.24)	60	5.69 (0.27)	2.60 (0.37)	54	55
7-15	6.17 (1.03)	2.69 (0.34)	55	5.28 (0.57)	2.49 (0.25)	52	6.97 (0.21)	2.92 (0.31)	58	5.81 (0.27)	2.62 (0.23)	55	55
8-1	6.02 (0.99)	2.48 (0.13)	58	4.70 (0.60)	2.37 (0.32)	49	5.88 (0.33)	3.02 (0.17)	48	5.52 (0.35)	2.94 (0.30)	46	50
8-16	5.96 (0.97)	2.72 (0.21)	53	4.47 (0.53)	2.35 (0.20)	47	5.00 (0.35)	3.11 (0.41)	37	5.36 (0.36)	2.77 (0.06)	48	46
9-1	5.60 (0.98)	2.42 (0.24)	55	3.89 (0.50)	2.10 (0.24)	46	4.10 (0.29)	2.52 (0.21)	38	4.87 (0.48)	2.45 (0.17)	49	47
9-11	5.46 (0.97)	2.51 (0.47)	54	3.68 (0.46)	2.05 (0.15)	43	3.91 (0.30)	2.27 (0.21)	42	4.64 (0.56)	2.29 (0.14)	50	47
9-21	4.49 (0.73)	2.07 (0.10)	53	2.52 (0.79)	1.80 (0.17)	22	3.33 (0.36)	2.05 (0.20)	38	3.57 (0.82)	2.11 (0.22)	36	37
10-1	2.25 (0.41)	1.22 (0.15)	44	1.33 (0.36)	1.03 (0.12)	18	1.55 (0.33)	1.25 (0.08)	17	1.30 (0.42)	1.20 (0.12)	0.6	20
10-11	0.32 (0.11)	0.82 (0.06)	−185	0.25 (0.05)	0.62 (0.06)	−152	0.23 (0.04)	0.76 (0.04)	−244	0.21 (0.08)	0.78 (0.07)	−321	−226
10-21	0	0.68 (0.08)	—	0	0.55 (0.03)	—	0	0.74 (0.04)	—	0	0.67 (0.06)	—	—
Mean	3.69	1.96	—	2.79	1.76	—	3.73	2.14	—	3.28	1.98	—	—
CV (%)	64	40	—	67	41	—	64	41	—	65	40	—	—

Note: Values in parentheses are standard deviations. Dif. (%) = [($LAI_{dir} - L_e$)/(LAI_{dir})] × 100. CV, coefficient of variation.

Fig. 4. Scatter plots of direct estimates (LAI_{dir}) against indirectly estimated LAI (LAI_{DHP}) according to scheme A (i.e., uncorrected) for the ELO, GP, SP, and LLF.

Table 5. Regression analyses of direct and indirect estimates (LAI_{dir} and LAI_{DHP}, respectively) of the LAI for each correction scheme.

Correction scheme	m	k	R^2	RMSE	P value
Scheme A	1.2802	0.4107	0.85	0.32	<0.001
Scheme B					
a	0.5504	0.8373	0.86	0.37	<0.001
b	0.5244	0.9068	0.85	0.46	<0.001
c	0.7511	0.8121	0.86	0.52	<0.001
Scheme C					
a	1.5544	0.5699	0.87	0.58	<0.001
b	1.5487	0.6043	0.86	0.69	<0.001
c	1.9091	0.5951	0.86	0.55	<0.001
Scheme D					
a	0.8262	1.0579	0.90	0.78	<0.001
b	0.5691	1.2628	0.88	0.96	<0.001
c	0.9797	1.0119	0.90	0.90	<0.001

Note: $LAI_{DHP} = mLAI_{dir}{}^k$, m and k are coefficients; $n = 300$. The a, b, and c indicate that the clumping index was calculated by the CC, LX, or CLX method in different schemes, respectively.

that the BAI represented a large proportion (70%–80%) of the total WAI in temperate deciduous forests.

After accounting for seasonal changes in woody materials, clumping effects, and automatic exposure in scheme D, the mean difference between LAI_{DHP-CC} estimates and LAI_{dir} is 7%. The strongest relationship between LAI_{dir} and corrected LAI_{DHP-CC} is found by using this scheme, with $R^2 = 0.90$. Despite the factors considered under scheme D, measurements were crude, particularly for the WAI. Thus, the contribution of WAI to LAI as the season progresses requires further study because the WAI contribution is of major importance during spring and autumn. Additionally,

LAI_{DHP-CC} from scheme D still underestimates LAI_{dir} by 11% in SP periods, indicating that the error is due to uncertainties other than the woody materials, clumping of leaves, and incorrect exposure setting.

One source of uncertainty in SP periods is the scheme D ratio of LAI_{DHP} to LAI_{dir}, which decreases significantly as the ratio of projected leaf width to characteristic leaf width increases. The characteristic leaf width values, taken from field data, are stable

Fig. 5. Scatter plots of direct estimates (LAI_{dir}) against indirectly estimated LAI (LAI_{DHP}) according to scheme B, scheme C, and scheme D for the ELO, GP, SP, and LLF. A lowercase a, b, or c (lower right corner of plots) indicates that the clumping index was calculated by the CC, LX, or CLX method in different schemes, respectively.
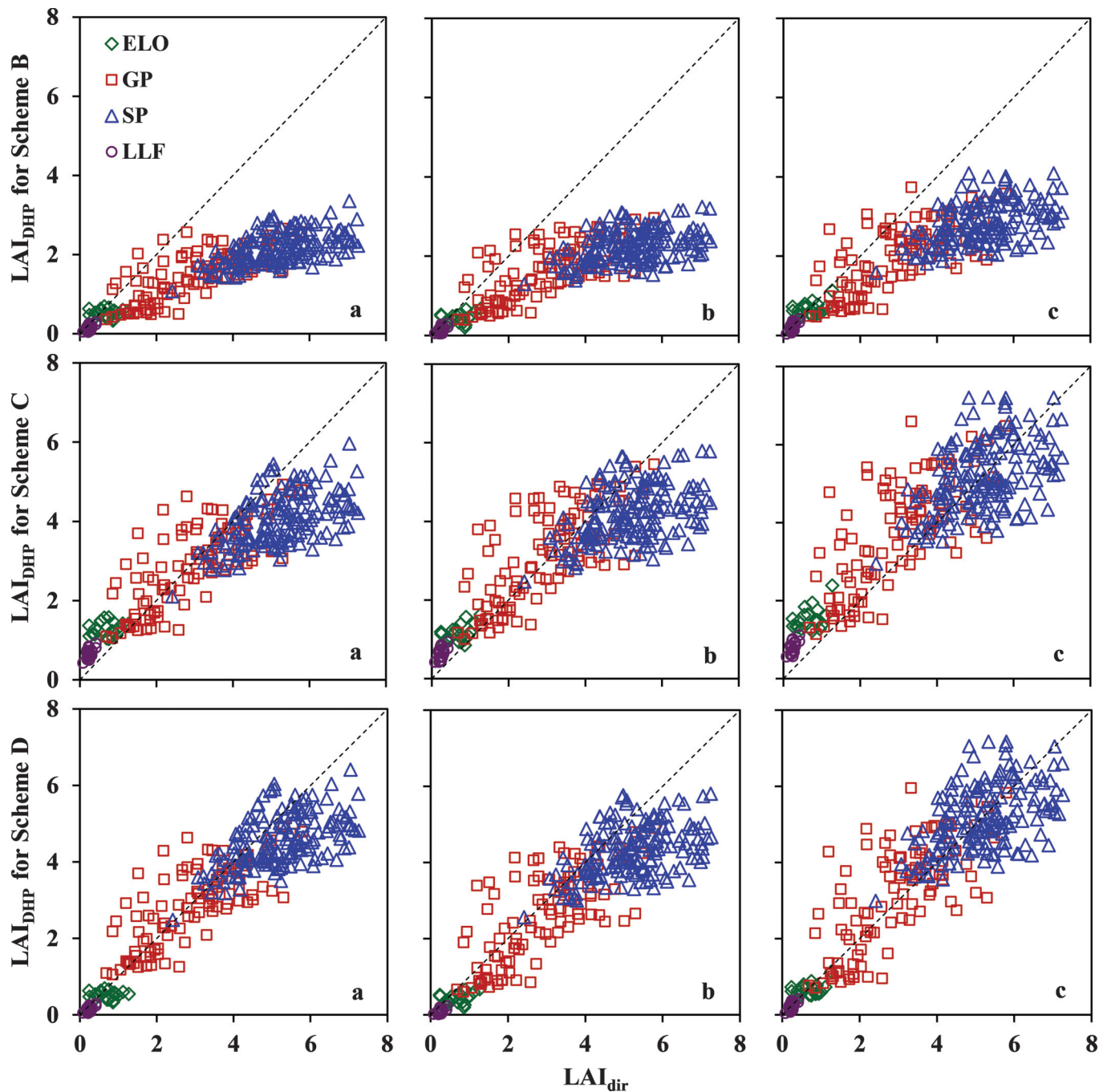
because the leaves are mature in the SP periods; however, increases in projected leaf width are automatically calculated by DHP-TRAC software (e.g., Chen and Cihlar 1995*b*). Very often, the projected leaf width automatically determined by the software is larger than the width of individual leaves in broadleaf forests, indicating that leaves often appear in tight groups that are not separated by the gap size distribution measured by DHP. This indicates a level of clumping that is not measured by the instrument, causing underestimation of LAI. Therefore, treating individual broad leaves as foliage elements in estimating the LAI by optical methods sometimes may not be appropriate for broadleaf

forests where leaves tend to form distinct branch and subbranch structures. Further study is needed to address this issue.

5. Conclusions

Seasonal variation in the LAI was estimated by combining leaf seasonality observations with litter collection data in four deciduous broadleaf forest plots. LAI values from these data (i.e., LAI_{dir}) were used to evaluate the accuracy of optical LAI measurements (i.e., LAI_{DHP}). Uncorrected LAI_{DHP} for the four plots underestimates LAI_{dir} by 14%–55% from 21 May to 1 October and overestimates LAI_{dir} by 78% and 226% on 12 May and 11 October, respectively. A practical

LAI$_{DHP}$ correction scheme (scheme D) developed in this study yields the best estimates of the seasonal variations in LAI that exceeds an accuracy of 83%. This indicates that the DHP method is useful for estimating seasonal changes of LAI in deciduous broadleaf forests, provided that appropriate corrections are made for incorrect exposure settings and canopy structure features such as the extents of the woody material contribution and foliage clumping.

Acknowledgements

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