

Evaluating optical measurements of leaf area index against litter collection in a mixed broadleaved-Korean pine forest in China

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Abstract

Key message We evaluated the error caused by optical measurements of leaf area index using a direct method in a mixed broadleaf-coniferous forest in China.

Abstract Indirect optical methods to measure leaf area index (LAI) have been previously developed, but it is difficult to evaluate the accuracy of these methods in a mixed broadleaf-coniferous forest. In this study, the LAI in a mixed broadleaved-Korean pine (*Pinus koraiensis*) forest in China was estimated directly by litter collection (LAI_{lit}) for the purpose of evaluating optical LAI measurements using digital hemispherical photography (DHP) and LAI-2000. With the DHP method, we corrected a systematic error due to incorrect automatic photographic exposure. With both DHP and LAI-2000 methods, we studied the

influences of zenith angle selection schemes (0° – 45° , 30° – 60° , 45° – 60° and 0° – 75°) on the effective LAI (L_e) measurement. In addition to optical L_e , we also investigated other major factors influencing the determination of LAI, including woody-to-total area ratio (α), element clumping index (Ω_E) and needle-to-shoot area ratio (γ_E). A significant correlation ($P < 0.01$) was observed between optical (DHP and LAI-2000) and litter collection methods, but DHP L_e underestimated LAI_{lit} by 61 % on average based on different zenith angle ranges, and L_e at 45° – 60° agrees better with LAI_{lit} ($R^2 = 0.75$, $P < 0.01$ and $RMSE = 4.5$), and the accuracy was enhanced by 21 % on average after considering α , Ω_E and γ_E and was further improved by 36 % after correcting for the error due to exposure. In contrast, LAI-2000 L_e underestimated LAI_{lit} by 32 % on average based on different zenith angle ranges, and L_e in rings 1–3 is closer to LAI_{lit} ($R^2 = 0.80$, $P < 0.01$ and $RMSE = 2.1$) than those in other rings (e.g., 3–4, 4 and 1–5), and after correcting for α , Ω_E and γ_E , the difference between LAI-2000 LAI and LAI_{lit} was less than 6 %. Although DHP L_e underestimated LAI-2000 L_e by an average of 43 % at different zenith angle ranges, significant correlations between them were found (minimum $r = 0.787$, $P < 0.01$). We confirm the accuracy of the best estimates of LAI using DHP and LAI-2000 methods are to be over 94 % after considering woody materials and foliage clumping within shoots and the canopy. Meanwhile, the litter collection method is useful for estimating LAI in a mixed broadleaf-coniferous forest, if the specific leaf area for all major species and the average leaf age for evergreen coniferous species are known.

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Introduction

Leaf area index (LAI) is a commonly used parameter for quantifying canopy structure and is defined as half the total leaf area per unit ground surface area (Chen and Black 1992). LAI influences the canopy microclimate, precipitation interception, distribution of solar radiation in the canopy, gas and energy exchanges between vegetation and the atmosphere (Bréda 2003; Bequet et al. 2011; Cutini et al. 1998; Sprintsin et al. 2007; Sea et al. 2011). Also, accurate measurements of LAI are essential for modeling carbon, nutrient, water, and energy cycles for terrestrial ecosystems (Brantley and Young 2007; Behera et al. 2010; Deblonde et al. 1994; Gonsamo and Chen 2014).

In recent years, many LAI indirect measurement techniques have been reported and theories behind these techniques are becoming mature (Chen et al. 2006; Jonckheere et al. 2004). In these widely used techniques, LAI is inferred based on gap fraction or gap size distribution within a canopy using radiative transfer theories (Ross 1981). Of all the techniques available for measuring gap fraction, the digital hemispherical photography (DHP) and LAI-2000 plant canopy analyzer (Licor Inc., Lincoln, NE, USA) are particularly attractive because they can simultaneously measure the canopy gap fraction from several zenith angles. However, woody materials and foliage clumping effects (both beyond and within shoots) have also been identified as important issues associated with the use of these optical techniques in the field (Chen 1996; Chen et al. 1997; Richardson et al. 2011). Chen (1996) confirmed that optical measurements corrected by woody materials and clumping effects could produce more accurate LAI values for conifers stands than destructive sampling methods. For deciduous broadleaf forests, optical LAI measurements can be validated using litter fall collection, which may be regarded as a direct LAI measurement method, but the validation using litter fall data is much more difficult in a broadleaf-coniferous mixed forest and has not been done previously to our knowledge. Moreover, woody materials (quantified by woody area index, WAI) and green leaves cannot be easily distinguished using optical methods, and therefore, alternative term has been proposed in the literature such as effective LAI (L_e) (Chen and Black 1992) to describe LAI estimates derived optically. Additionally, a remaining error in optical LAI measurements lies in selecting zenith angles reasonably in data processing. Many different zenith angle ranges were used to estimate LAI such as 0°–45° (Chen et al. 2006; Sonnentag et al. 2007), 0°–60° (Chason et al. 1991; Liu et al. 2012), 30°–60° (Gonsamo et al. 2010), and 45°–60° (Eriksson et al. 2005) or at a single zenith angle at or near 57.5° (Leblanc et al. 2005; Macfarlane et al. 2007).

In comparison to the LAI-2000 instrument, the accuracy of LAI measured using DHP is affected by the additional issue of photograph exposure setting, because it influences the differentiation between green leaves and the background (sky). Incorrect exposure has been demonstrated as a major cause of LAI measurement errors (Chen et al. 1991; Englund et al. 2000; Song et al. 2014; Wagner 1998), because it can decrease the contrast between sky and foliage and further affect the calculation of LAI by the DHP software.

Direct methods include harvesting, allometry and litter collection (Bréda 2003; Gower and Norman 1991; Ryu et al. 2010). The first method can be accurate, but is destructive and time-consuming. The allometry method requires pre-established allometric relationships between leaf area and stem diameter of trees, which are often established through destructive sampling. Litter collection is then the only non-destructive and direct method for LAI estimation. It is traditionally adapted to deciduous forest habitats (e.g., Dufrière and Bréda 1995; Eriksson et al. 2005; Neumann et al. 1989), but some researchers measured the annual maximum LAI (LAI_{max}) of evergreen conifer forests by combining annual litter fall values with the average life span of fallen evergreen needles. This method was used by Marshall and Waring (1986) to measure LAI of a douglas-fir (*Pseudotsuga menziesii*) stand in the western Cascade Mountains; Sprintsin et al. (2011) also studied LAI of an aleppo pine (*Pinus halepensis*) plantation using the litter collection method. Therefore, it is also possible and reasonable to measure LAI using the litter collection method in a mixed broadleaf-coniferous forest.

Good correlations between indirect LAI (optical) and direct LAI (e.g., litter collection) have been widely reported by many previous studies. For instance, Chason et al. (1991) reported the relationship between LAI from litter collection (LAI_{lit}) and LAI derived from LAI-2000 ($LAI_{LAI-2000}$) in a mixed deciduous forest stand as follow: $LAI_{lit} = 1.86 \times LAI_{LAI-2000}$ with $R^2 = 0.97$; Cutini et al. (1998) found that $LAI_{LAI-2000}$ was always below LAI_{lit} , but the correlation between the two data sets was linear and significant, with $LAI_{LAI-2000} = 0.56 LAI_{lit} + 0.88$ ($R^2 = 0.52$, $P < 0.00001$); and Kalácska et al. (2005) reported that the optical (e.g., LAI-2000) LAI after correcting for the WAI had a strong relationship with LAI_{lit} , with an overall relationship of $y = 0.37x + 1.09$ ($R^2 = 0.78$), where y is $LAI_{LAI-2000}$ and x is LAI_{lit} . However, few studies are reported to evaluate the accuracy of optical LAI after considering above mentioned factors (e.g., woody materials, clumping effects, zenith angles or exposure) against a direct method, especially in a mixed broadleaf-coniferous forest stand.

In the present study, we directly estimated the LAI_{max} using a litter collection method in the mixed broadleaved-Korean pine (*Pinus koraiensis*) forest in China. Meanwhile, we estimated L_e using optical DHP and LAI-2000 methods. Therefore, the objectives of this study were (1) to compare L_e derived from DHP and LAI-2000 methods with different zenith angle ranges, (2) to evaluate factors (e.g., woody materials, clumping effect, exposure setting and zenith angles) that influence optical LAI measurements using litter collection data.

Materials and methods

Study site description

The study site is an old-growth mixed broadleaved-Korean pine forest in the Liangshui National Nature Reserve of the Xiaoxing'an Mountains in Northeastern China (47°10'50"N, 128°53'20"E). The reserve covers 12,133 ha with about 1.7 million m³ of growing stock and 98 % forest canopy coverage. The complex topography includes mountains ranging up to 707.3 m above sea level. The mean annual temperature is −0.3 °C, with a highest mean temperature of 7.5 °C and lowest mean temperature of −6.6 °C. The mean annual precipitation is 676 mm. Snow covers the site for 130–150 days a year and the frost-free period is 100–120 days.

Methods

Study points

The study was conducted in a 9 ha (300 m × 300 m) mixed broadleaved-Korean pine forest dynamic plot, divided into 900 sub-plots (10 m × 10 m). We measured diameter at breast height (DBH) and tree height and recorded the coordinates of all trees with DBH ≥ 1 cm in each sub-plot (for basic parameters see Table 1). Aluminum tree tags with tree numbers were nailed at 1.4 m above the ground. Tags were fixed by copper wire rather than nails for plants with DBH < 8 cm to reduce the influence on plant growth. At the center (160 m × 160 m) of the permanent sampling plot, 64 litter traps were used at the same points on an 8 × 8 grid with 20 m spacing (Fig. 1). Litter traps were supported with 8 mm diameter wires and covered with nylon mesh (pore size 1 mm, depth 0.5–0.6 m). Each litter trap had a square aperture of 0.5 m² and its base was about 0.5 m above the ground.

Observations of L_e using optical methods

Hemispherical photographs of the sample points were taken using a WinSCANOPY 2006 Plant Canopy Analyzer (Regent, Instruments, Inc., Quebec, Canada; contains a digital camera (Coolpix 4500, Nikon, Tokyo, Japan), and a 180° fisheye lens (Nikon FC-E8)) in early August 2009 (the

Table 1 Species composition and specific leaf area (SLA) for major species in the mixed broadleaved-Korean pine dynamic monitoring plot in the Xiaoxing'an Mountains, China

Major species	Density (trees ha ⁻¹)	Mean DBH (cm)	Basal area (m ² ha ⁻¹)	Importance value (%)	SLA (cm ² g ⁻¹)
<i>Pinus koraiensis</i>	133	42.81	24.15	23.33	83.79 (3.74)
<i>Abies nephrolepis</i>	101	16.17	3.01	5.77	80.80 (5.43)
<i>Picea</i> spp.	20	18.99	1.06	1.79	59.41 (9.70)
<i>Tilia amurensis</i>	81	13.35	3.01	5.13	243.59 (14.26)
<i>Acer mono</i>	238	7.73	2.43	8.25	305.04 (50.08)
<i>Betula costata</i>	67	13.02	2.04	3.73	199.79 (11.55)
<i>Ulmus laciniata</i>	108	7.73	1.48	4.65	261.40 (5.65)
<i>Fraxinus mandschurica</i>	45	12.54	1.27	2.61	338.36 (13.63)
<i>Acer tegmentosum</i>	110	5.1	0.49	3.58	263.26 (32.66)
<i>Acer ukurunduense</i>	140	4.26	0.43	4.38	350.67 (8.56)
<i>Corylus mandshurica</i>	513	2.1	0.38	10.5	374.89 (66.93)
<i>Ulmus japonica</i>	44	5.11	0.29	1.42	179.35 (18.05)
Others	773	2.86	2.26	24.86	–
Total	2,373	7.41	42.3	100	–

DBH means diameter at breast height; and numbers in parentheses are standard deviations across different sample periods

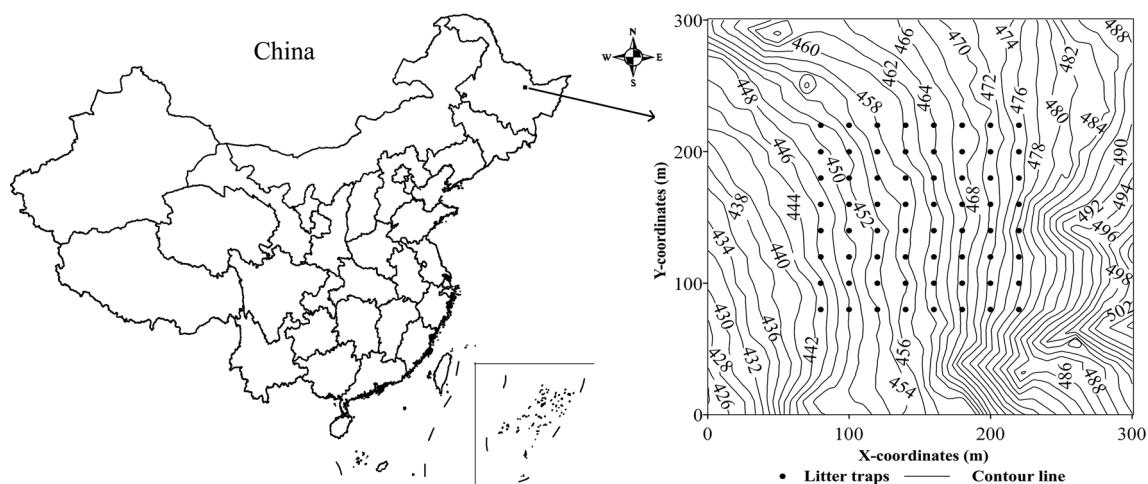


Fig. 1 The location and contour map of the 9 ha (300 m × 300 m) mixed broadleaved-Korean pine dynamic monitoring plot in the Xiaoxing'an Mountains, China

period for the LAI_{max}). The camera was held 1.3 m above the ground using a tripod. To avoid direct sunlight, a total of 64 hemispheric photographs in the stand were taken under an evenly overcast sky with automatic exposure. A LAI-2000 unit was operated subsequently at the same photographic spots for comparison with DHP, and the second LAI-2000 unit, cross-calibrated with the former, was used to automatically record “above-canopy” readings from a nearby clearing. A 90° view cap was used on both units to avoid the influence of the operator on the sensor.

To obtain more accurate LAI (L), three corrections must be made to L_e (Chen 1996):

$$L = (1 - \alpha)L_e \frac{\gamma_E}{\Omega_E} \quad (1)$$

where α is the woody-to-total area ratio; L_e is the effective leaf area index that directly obtained from optical instruments measuring the canopy gap fraction; Ω_E is the clumping index, quantifies the effect of foliage clumping effect beyond the shoots and has been usually measured based on gap size distribution using the Tracing Radiation and Architecture of Canopies instrument (TRAC; 3rd Wave Engineering, ON, Canada) or DHP-TRAC (Chen and Cihlar 1995; Leblanc et al. 2005); γ_E is the needle-to-shoot area ratio, quantifies the effect of foliage clumping within the shoots. For broadleaf species, individual leaves are considered as foliage elements, and $\gamma_E = 1.0$, but for coniferous species, it is usually larger than 1.0.

An image software (Adobe Photoshop CS6, Adobe Systems Incorporated, North America) was used to calculate α . We measured α value of each hemispherical photo as follows: First, the total LAI (LAI_{total}) of leaves and woody materials of each hemispherical photo was

measured with DHP software; Second, the Clone Stamp Tool in the image software was used to replace the woody materials (e.g., stems) with sky, leaving only leaves on the photos (Qi et al. 2013), then reprocessed the photo using DHP software and derived LAI of leaves (LAI_{leaf}); Third, the woody-to-total area ratio (α) was then derived accordingly: $\alpha = (LAI_{total} - LAI_{leaf})/LAI_{total}$. Ω_E was derived through the DHP-TRAC software (Chen et al. 2006) within the zenith angle range 40°–45°. γ_E for three evergreen conifers (*Pinus koraiensis*, *Abies nephrolepis*, and *Picea* spp.) in the stand were quantified in early August 2009. To obtain an average value for a stand, for each species, 27 shoot samples were taken from three trees: one dominant (D, DBH ≥ 40 cm), one co-dominant (M, 20 ≤ DBH < 40 cm) and one suppressed (S, DBH < 20 cm), at three heights: top (T), middle (M) and low (L), creating nine classes containing three shoot samples each: DT, DM, DL, MT, MM, ML, ST, SM, and SL. These sample shoots were analyzed according to the volume replacement method proposed by Chen (1996), and implementation details referred to Liu et al. (2012). To obtain the γ_E for each sample point in the stand, the γ_E was derived as the weighted average between broadleaf species ($\gamma_E = 1.0$) and coniferous species ($\gamma_E > 1.0$, measured in this study). The weights between these two types of species were obtained through basal area measurements in 400 m² (20 m × 20 m, as centered on each sample point).

Observation of specific leaf area

Specific leaf area (SLA) is defined as the total leaf area per unit of dry weight (Eriksson et al. 2005). In order to determine the SLA of each major species, we sampled the leaves (needles) from August to November in 2012, once a

month. We measured SLA for broadleaf and coniferous species through different methods. For each broadleaf species, 10–70 flat leaves (during late fall season, the fallen leaves was little) in the litter traps were randomly selected in each sampling period. The area of each flat leaf was measured with an image scanner (Model 5560; BenQ Corporation, China) at 300 dpi resolution. For coniferous species, we first selected 200–400 needles of each species from litter traps. Then the needle area was measured based on the volume displacement method (Chen 1996), and details referred to Liu et al. (2012). After area measurement, the samples were dried at 65 °C for 48 h to a constant weight, measured to the nearest milligram. The SLA for each species was obtained by dividing the dry mass by the leaf (needle) area. Potential interannual variability in the SLA was estimated to be insignificant.

Observation of LAI from the litter collection method

The LAI_{max} for broadleaf and coniferous species in the mixed broadleaved-Korean pine forest was measured using different methods. For broadleaf species, the total leaf area at each litter trap was calculated by adding the leaf areas of the fallen leaves of each species from mid-August to mid-November and then dividing by the area of litter trap derived the LAI_{max}:

$$LAI_{max} = \sum W_i \times SLA/A \tag{2}$$

where W_i is the dry mass of fallen leaves in i sampling period, SLA is the specific leaf area, and A is the area of the litter trap.

For evergreen conifers, the total LAI in the canopy was obtained as:

$$LAI_{i-total} = \sum_{i=1}^n LAI_i \tag{3}$$

where $LAI_{i-total}$ is the total LAI that remains in the canopy after year i , LAI_i is the LAI that remains in the canopy after year i , and i is the number of years after the needle emergence. Assuming new LAI is the same each year, a measurement of LAI_i in any year represents the average condition. Thus, the LAI from the needle falls in year i equals $LAI_{i-1} - LAI_i$. The average leaf age (\overline{Age}) (i.e., leaf life span) of LAI of the litter fall is a weighted average of LAI that falls at different years, i.e.,

$$\overline{Age} = \sum_{i=2}^n \frac{LAI_{i-1} - LAI_i}{LAI_{i=1}} \times (i - 1) \tag{4}$$

The survival ratio of needle in year i was used to represent the LAI _{i} in the canopy. The needle survival ratio of *Pinus koraiensis*, *Abies nephrolepis*, and *Picea* spp. were measured in the field from branch samples. The sample

scheme was the same as that for measuring the γ_E . For each coniferous species, we obtained 54 branch samples from three trees and separate them into nine classes (i.e., DT, DM, DL, MT, MM, ML, ST, SM, and SL). In the laboratory, all needles were subsequently removed and separated into 1-year-old (the leaf age of current-year needles was defined as 1-year-old in this study), 2-year-old, etc. We recorded the total numbers of needles of different ages in each sample branch, from the youngest with the largest number of needles to the oldest with a few needles. Then, we calculated the survival ratio of needles of different ages by normalizing these numbers against the youngest needle number so that the largest value became 1.0. Thus, \overline{Age} of each tree was obtained using Eq. (4). The mean \overline{Age} of each species in the stand was derived by weighting the mean age in each of the three DBH classes against the total basal area of the species in each class.

Therefore, the LAI_{max} of evergreen coniferous species is obtained from multiplying the LAI from the litter fall within a certain period (1 year) by the average leaf age for each species. Finally, the LAI_{max} for the stand could be obtained by combining broadleaf with coniferous species.

Leaf litter was trapped from mid-August 2009 to early August 2010. The first litter collection in early August 2009 was used to remove the old litter in traps, not to estimate the LAI_{max} in the stand. It was collected about every 2 weeks from mid-August 2009 to mid-November 2009, four times from December 2009 to early August 2010, and once a month from May to August 2010. During each litter collection, we sorted the leaves of each species in each litter trap and then weighed the litter by species; the sampled leaves (needles) were then dried at 65 °C for 48 h and the total dry mass of all the leaves (needles) was obtained. The LAI_{max} values for broadleaf and coniferous species were measured using the litter from different time periods: from mid-August 2009 to mid-November 2009 for broadleaf species and from mid-August 2009 to early August 2010 for coniferous species. Summation of these LAIs gave us a measurement of the LAI_{max} in the stand.

Statistical processing of data

The hemispherical photographs were processed with the DHP software to derive the L_e (Leblanc et al. 2005), in processing with zenith angle ranges of 0°–45°, 30°–60°, 45°–60° and 0°–75°. LAI-2000 data were processed using the available C2000 software, corresponding to the zenith angle ranges of the DHP method, rings 1–3, 3–4, 4 and 1–5 were selected, respectively. Since all hemispherical photographs were taken with automatic exposure that caused considerable underestimation of L_e , and L_e was corrected based on the relationship between DHP L_e obtained with

automatic exposure and LAI-2000 L_e reported by Zhang et al. (2005). Statistically significant differences among different needle-to-shoot area ratios for coniferous species were detected by one-way ANOVA test (e.g., the least significant difference, LSD) on the level $\alpha = 0.05$. Pearson's correlation coefficient (r) between two optical methods was calculated. Linear correlations between LAI values derived from the litter collection and optical methods were developed, and the coefficient of determination (R^2), the root mean square error (RMSE) and the P values were calculated. All statistical analyses were conducted with SPSS 18 statistical software (SPSS Inc., Chicago, IL, USA).

Results

The average leaf age for coniferous species

Generally, the $\overline{\text{Age}}$ of *Picea* spp. and *Abies nephrolepis* were larger than *Pinus koraiensis* (Table 2). For *Pinus koraiensis*, the $\overline{\text{Age}}$ for suppressed tree was the largest with a mean value of 3.25 (SD = 0.46), followed by the dominant tree and co-dominant tree, with mean values of 3.18 (0.36) and 2.79 (0.39), respectively. There was no clear difference among the different trees for *Picea* spp., with mean values of 3.95 (0.61), 3.86 (0.61) and 3.91 (0.41) for dominant, co-dominant and suppressed trees, respectively. In contrast, the suppressed tree for *Abies nephrolepis* had the largest mean $\overline{\text{Age}}$ of 4.10 (0.80), and the $\overline{\text{Age}}$ for dominant tree was the lowest with a mean value of 3.38 (0.83).

Table 2 The average leaf age and standard deviation of each evergreen coniferous species in the mixed broadleaved-Korean pine dynamic monitoring plot in the Xiaoxing'an Mountains, China

Species	Dominant	Co-dominant	Suppressed
<i>Pinus koraiensis</i>			
Top	3.25 (0.29)	2.69 (0.47)	3.48 (0.61)
Middle	3.17 (0.53)	2.71 (0.41)	3.21 (0.42)
Low	3.14 (0.27)	2.97 (0.24)	3.07 (0.30)
Mean	3.18 (0.36)	2.79 (0.39)	3.25 (0.46)
<i>Picea</i> spp.			
Top	3.63 (0.57)	3.50 (0.54)	3.66 (0.45)
Middle	3.87 (0.56)	4.11 (0.65)	4.05 (0.31)
Low	4.35 (0.57)	3.98 (0.52)	4.01 (0.39)
Mean	3.95 (0.61)	3.86 (0.61)	3.91 (0.41)
<i>Abies nephrolepis</i>			
Top	3.11 (0.94)	3.87 (0.34)	4.35 (0.63)
Middle	3.28 (0.77)	3.25 (0.40)	4.63 (0.54)
Low	3.69 (0.84)	3.65 (0.80)	3.33 (0.60)
Mean	3.38 (0.83)	3.59 (0.58)	4.10 (0.80)

LAI for major species

LAI_{max} was 7.03 ± 0.27 (mean \pm SE) for the mixed broadleaved-Korean pine forest using the litter collection method. LAI of *Pinus koraiensis* accounted for the largest proportion for both coniferous species and all species (the ratios were $82.24 \pm 1.96\%$ and $49.88 \pm 2.47\%$, respectively) (Table 3), which was closely related to *Pinus koraiensis* with high relative dominance (57.09%). The coniferous species accounted for a larger proportion (59.20%) than broadleaf species (40.80%). For broadleaf species, *Acer mono* accounted for the largest proportion ($9.15 \pm 1.16\%$), followed by *Tilia amurensis* ($7.41 \pm 1.05\%$), indicating that they were the major species associated with *Pinus koraiensis* in the stand. However, the mean DBH and basal area of *Tilia amurensis* were all larger than *Acer mono*, suggesting that LAI was also affected by other factors (e.g., SLA, and density). For all major species, *Ulmus japonica* and *Acer tegmentosum* accounted for the smallest proportions of the total LAI, only $0.96 \pm 0.36\%$ and $0.66 \pm 0.21\%$, respectively.

Table 3 Annual maximum LAI (LAI_{max}) derived from the litter collection and LAI percentage for major species in the mixed broadleaved-Korean pine dynamic monitoring plot in the Xiaoxing'an Mountains, China ($n = 64$)

Major species	LAI _{max} (m ² m ⁻²)	Percentage ^a (%)	Percentage ^b (%)
<i>Pinus koraiensis</i> ^c	3.65 (0.28)	82.24 (1.96)	49.88 (2.47)
<i>Abies nephrolepis</i> ^c	0.34 (0.03)	9.79 (1.06)	5.15 (0.50)
<i>Picea</i> spp. ^c	0.27 (0.03)	7.97 (0.94)	4.17 (0.44)
<i>Acer mono</i>	0.60 (0.07)	22.34 (2.05)	9.15 (1.16)
<i>Tilia amurensis</i>	0.48 (0.07)	18.11 (2.37)	7.41 (1.05)
<i>Fraxinus mandschurica</i>	0.34 (0.07)	9.93 (1.90)	4.67 (0.96)
<i>Ulmus laciniata</i>	0.28 (0.05)	10.44 (1.76)	3.93 (0.73)
<i>Betula costata</i>	0.25 (0.05)	9.70 (1.85)	3.79 (0.72)
<i>Acer ukurunduense</i>	0.25 (0.05)	9.06 (1.68)	3.65 (0.72)
<i>Corylus mandshurica</i>	0.17 (0.04)	5.56 (1.42)	2.13 (0.49)
<i>Ulmus japonica</i>	0.07 (0.03)	2.13 (0.83)	0.96 (0.36)
<i>Acer tegmentosum</i>	0.05 (0.02)	1.86 (0.69)	0.66 (0.21)
Others ^d	0.28 (0.04)	10.87 (1.50)	4.46 (0.72)
Total	7.03 (0.27)	–	100

Parenthetical values show standard error, SE

^a Accounted for the proportion of total LAI for coniferous or broadleaf species, respectively

^b Accounted for the proportion of total LAI for all species

^c LAI for coniferous species in the entire life span

^d Represented other broadleaf species

Main correction parameters for the optical methods

All parameters required for LAI estimation using Eq. (1) are summarized in Table 4. The mean error caused by woody materials was 3.0 % (SD = 2.6), and the distribution of α showed strong spatial heterogeneity among all sample points, just as the maximum α was 15.5 % and the minimum value was 0.2 %. The mean Ω_E directly from DHP-TRAC was 0.90 ± 0.05 , and the biggest difference among all points was 0.24, the maximum and minimum values were 0.99 and 0.75, respectively. The maximum γ_E value was 1.64, the minimum 1.03, and the mean was 1.43 ± 0.15 .

The variations of measured γ_E of different canopy levels for three coniferous species were shown in Fig. 2. For three species, the variations of γ_E among the different levels of shoot samples showed similar patterns: the values of dominant trees were generally larger than co-dominant and suppressed trees significantly ($P < 0.05$), and those of co-dominant trees were larger than those of suppressed, but there was no significant difference between them ($P > 0.05$). In general, *Pinus koraiensis* has the largest γ_E value, which is significantly larger than other species ($P < 0.05$). *Picea* spp. and *Abies nephrolepis* have the second and third largest γ_E values, respectively.

Comparison of L_e from optical measurements (DHP and LAI-2000)

We carried out point-by-point comparison of L_e measurements by both DHP and LAI-2000 for all available sample points. For the convenience of comparison, the same zenith angle ranges were chosen for both sets of measurements. Generally, significant correlations were found between L_e estimates from DHP and from LAI-2000 (minimum $r = 0.787$, $P < 0.01$) based on different zenith angle ranges. However, DHP L_e was lower than LAI-2000 L_e at all zenith angle ranges, and DHP L_e in the angle ranges of 0° – 45° , 30° – 60° , 45° – 60° and 0° – 75° underestimated LAI-2000 L_e by 47 ± 9 % (mean \pm SD), 40 ± 8 , 38 ± 7 and 45 ± 10 %, respectively (Table 5). DHP L_e at different zenith angle ranges did not differ from each other markedly (coefficient of variation = 7.7 %), and had the maximum value (2.76 ± 0.68) at 45° – 60° and the minimum (2.32 ± 0.53) at 0° – 75° . The order of LAI-2000 L_e based on different zenith angle ranges was rings 1–3 (5.16 ± 1.44) > rings 3–4 (4.62 ± 1.29) > ring 4 (4.51 ± 1.25) > rings 1–5 (4.38 ± 1.19). There was also no clear difference among LAI-2000 L_e within different zenith angle ranges (coefficient of variation = 7.4 %), but it had the maximum value (5.16 ± 1.44) based on rings 1–3, not the same as DHP (45° – 60°). It is interesting to note that both DHP and LAI-2000 provide the minimum

Table 4 Woody-to-total area ratio (α), clumping index (Ω_E) and needle-to-shoot area ratio (γ_E) for the mixed broadleaved-Korean pine dynamic monitoring plot in the Xiaoxing’an Mountains, China

Parameters	Maximum	Minimum	Mean \pm SD	Sample points
α (%)	15.5	0.2	3.0 ± 2.6	64
Ω_E	0.99	0.75	0.90 ± 0.05	64
γ_E	1.64	1.03	1.43 ± 0.15	64

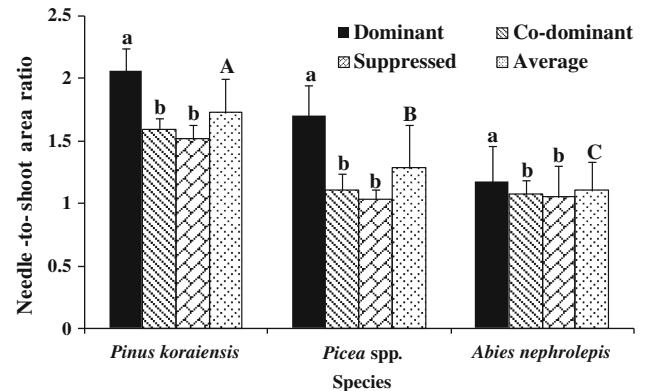


Fig. 2 Needle-to-shoot area ratios (γ_E) of coniferous species in the mixed broadleaved-Korean pine dynamic monitoring plot in the Xiaoxing’an Mountains, China. For each species, 27 shoot samples were taken from three trees: one dominant (D), one co-dominant (M) and one suppressed (S), at three heights: top (T), middle (M) and low (L), creating nine classes containing three shoot samples each: DT, DM, DL, MT, MM, ML, ST, SM, and SL. Different lowercase letters within same species meant significant differences among γ_E of different leaves at $P < 0.05$ level. Different capital letters meant significant differences among average γ_E of different species at $P < 0.05$ level

value in the largest zenith angle range (0° – 75° or rings 1–5), indicating indeed that stronger multiple scattering effects existed at larger zenith angles (Chen et al. 2006).

L_e estimated from the DHP method versus LAI estimated from the litter collection method (LAI_{lit})

Figure 3 illustrates the correlation between LAI_{lit} and L_e from DHP within different zenith angle ranges (0° – 45° , 30° – 60° , 45° – 60° and 0° – 75°). For all zenith angle ranges, a significant correlation ($P < 0.01$) between LAI_{lit} and uncorrected L_e was observed (Fig. 3), with $R^2 = 0.71$ at 0° – 45° , $R^2 = 0.64$ at 30° – 60° , $R^2 = 0.75$ at 45° – 60° , and $R^2 = 0.67$ at 0° – 75° . The RMSE value at 0° – 75° (4.9) was larger than those in other angle ranges (ranging from 4.5 to 4.6), indicating that the 45° – 60° zenith angle range was the best choice to estimate L_e when the DHP method is used. Nevertheless, a bias from the 1:1 relationship was present, with L_e values always below LAI_{lit} values for all zenith angle ranges. In absolute values, the tendency of DHP to

Table 5 Comparison of effective leaf area index (L_e) derived from digital hemispherical photography (DHP) and LAI-2000 methods ($n = 64$)

	DHP L_e 0°–45°	LAI-2000 L_e Rings 1–3	Differ. (%)	DHP L_e 30°–60°	LAI-2000 L_e Rings 3–4	Differ. (%)	DHP L_e 45°–60°	LAI-2000 L_e Ring 4	Differ. (%)	DHP L_e 0°–75°	LAI-2000 L_e Rings 1–5	Differ. (%)	Mean Difference (%)
Maximum	4.14	8.08	-66	3.97	7.06	-62	4.13	6.65	-50	3.88	6.54	-61	-57
Minimum	0.75	1.64	-22	0.90	1.43	-16	0.89	1.39	-19	0.77	1.17	-7	-28
Mean	2.67	5.16	-47	2.73	4.62	-40	2.76	4.51	-38	2.32	4.38	-45	-43
SD	0.66	1.44	9	0.68	1.29	8	0.68	1.25	7	0.53	1.19	10	6
r	0.787**		-	0.841**		-	0.919**		-	0.824**		-	-

The difference was calculated by (DHP $L_e - \text{LAI-2000 } L_e$)/LAI-2000 L_e ; r Pearson's correlation coefficient; between DHP L_e and LAI-2000 L_e , and significance level: ** $P < 0.01$

underestimate LAI increased with increasing LAI. The average differences between two methods were $61 \pm 6\%$ at 0°–45°, $60 \pm 7\%$ at 30°–60°, $59 \pm 7\%$ at 45°–60°, and $65 \pm 6\%$ at 0°–75°, with an average of 61%.

Significant correlations ($P < 0.01$) between LAI_{lit} and L_e from the DHP method with consideration of woody-to-total area ratio, clumping index and needle-to-shoot area ratio ($LAI_{DHP-WCN}$) were observed at any zenith angle ranges (Fig. 4). In contrast to the uncorrected case (Fig. 3), R^2 values increased by an average of 0.16 at all zenith angle ranges, and RMSE values decreased at any ranges, by 1.6 at 0°–45°, 1.5 at 30°–60°, 1.6 at 45°–60°, and 1.3 at 0°–75°. The difference in LAI estimated using DHP within any zenith angle range reduced when woody materials and clumping effects were considered. However, underestimation was also present at all ranges, by $40 \pm 7\%$ at 0°–45°, $38 \pm 8\%$ at 30°–60°, $37 \pm 7\%$ at 45°–60°, and $46 \pm 8\%$ at 0°–75°. These results suggested that we could obtain the total error from woody-to-total area ratio, clumping index and needle-to-shoot area ratio to be 21, 22, 22 and 19%, respectively. The average sum of errors caused by woody materials and foliage clumping within the canopy was about 21%, indicating that the woody materials and foliage clumping are major influence factors for LAI measurement precision using the DHP method, but not enough to explain the difference between DHP LAI and litter collection LAI.

Significant correlations ($P < 0.01$) between LAI_{lit} and DHP L_e after correcting for the automatic exposure were observed at different zenith angle ranges (Fig. 5). In contrast to the uncorrected case (Fig. 3), the optical LAI values after correcting for the exposure were more close to LAI_{lit} . However, underestimation was also showed at all ranges, by $36 \pm 10\%$ at 0°–45°, $34 \pm 11\%$ at 30°–60°, $33 \pm 10\%$ at 45°–60°, and $44 \pm 10\%$ at 0°–75°, with an average of 37%. These results indicate that the exposure is another major influence factor for LAI measurement precision using DHP, just as the total contribution of woody materials and foliage clumping to LAI, the incorrect exposure alone was not enough to explain the difference between DHP LAI and litter collection LAI.

Significant correlations ($P < 0.01$) between LAI_{lit} and LAI from the DHP method after correcting for the woody-to-total area ratio, clumping index, needle-to-shoot area ratio and exposure ($LAI_{DHP-WCNE}$) were obtained at any zenith angle ranges (Fig. 6). After correcting the above factors, the accuracy of LAI from the DHP method was markedly improved, in spite of remaining underestimation by $10 \pm 13\%$ at 0°–75° (RMSE = 1.3), but the difference between LAI_{lit} and $LAI_{DHP-WCNE}$ was less than 5% on average based on different zenith angle ranges (0°–45°,

Fig. 3 Relationship between LAI estimated by litter collection (LAI_{lit}) and effective LAI from DHP with different zenith angle ranges. The dotted line indicates the 1:1 relationship

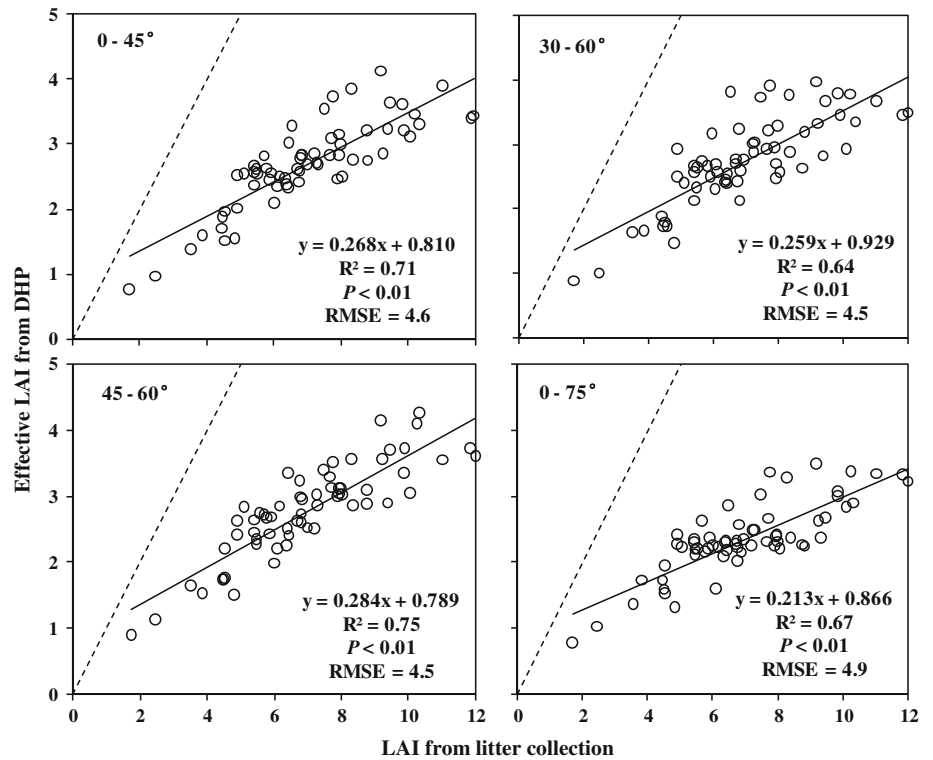
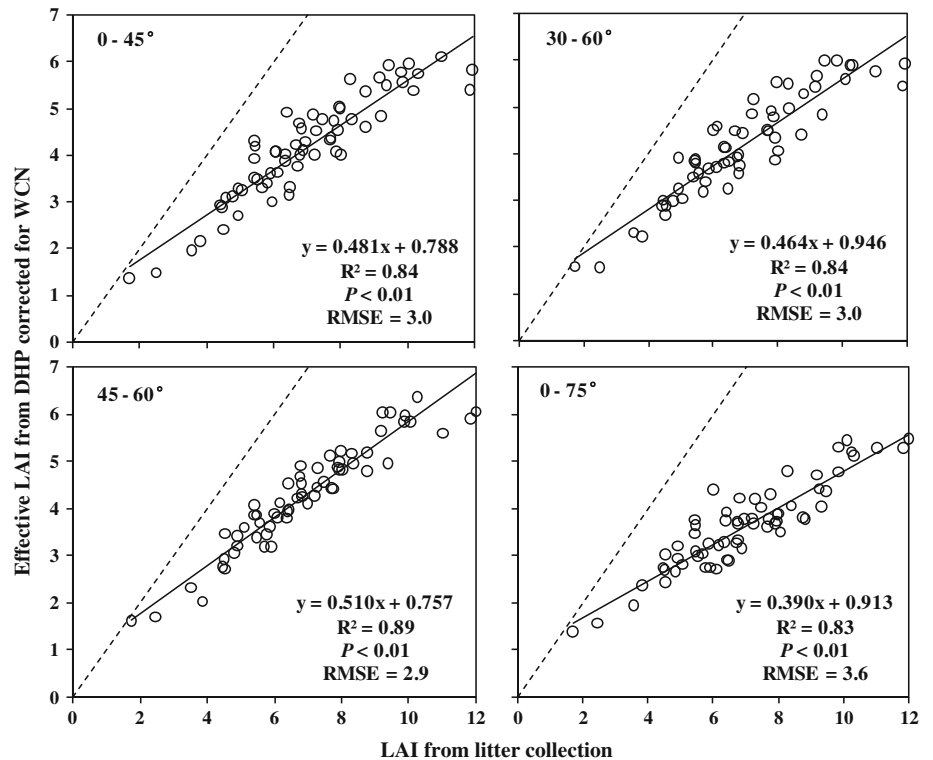


Fig. 4 Relationship between LAI estimated by litter collection (LAI_{lit}) and effective LAI from DHP after correcting for the woody-to-total area ratio (W), clumping index (C) and needle-to-shoot area ratio (N) ($LAI_{DHP-WCN}$) according to Eq. (1) with different zenith angle ranges. The dotted line indicates the 1:1 relationship



30°–60°, 45°–60° and 0°–75°). In contrast to considering the woody materials and foliage clumping alone, the accuracy of optical LAI after additionally considering the

exposure was enhanced by 39 % at 0°–45°, 35 % at 30°–60°, 32 % at 45°–60°, and 36 % at 0°–75°, with an average of 36 %.

Fig. 5 Relationship between LAI estimated by litter collection (LAI_{lit}) and effective LAI from DHP after correcting for the automatic exposure with different zenith angle ranges. The dotted line indicates the 1:1 relationship

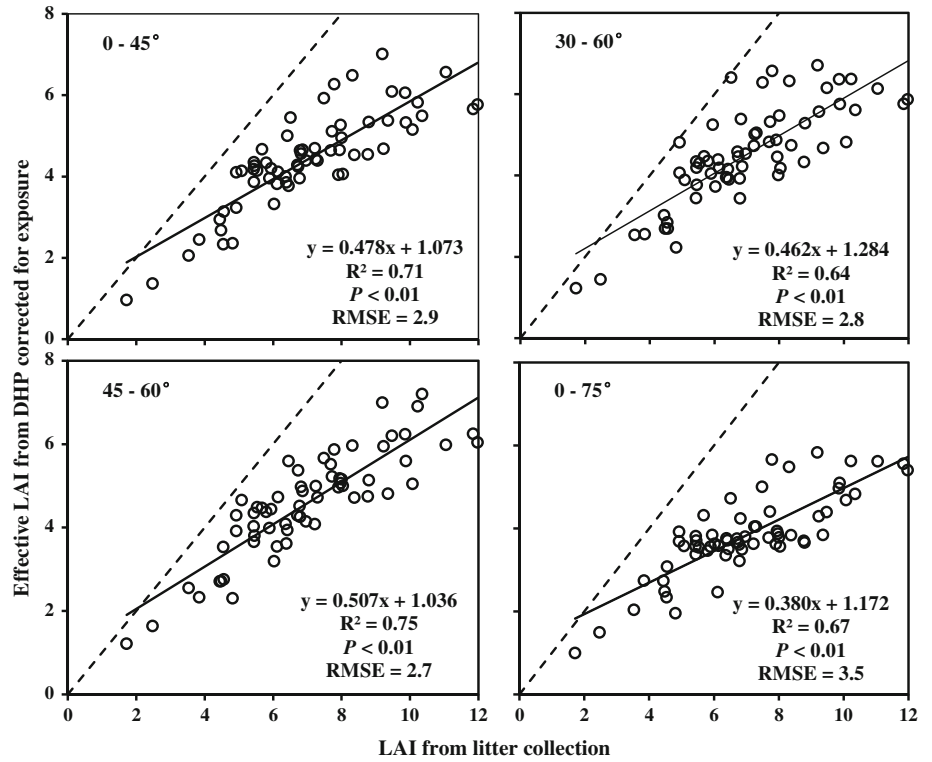


Fig. 6 Relationship between LAI estimated by litter collection (LAI_{lit}) and effective LAI from DHP after correcting for the woody-to-total area ratio (W), clumping index (C) and needle-to-shoot area ratio (N) and automatic exposure (E) ($LAI_{DHP-WCNE}$) with different zenith angle ranges. The dotted line indicates the 1:1 relationship

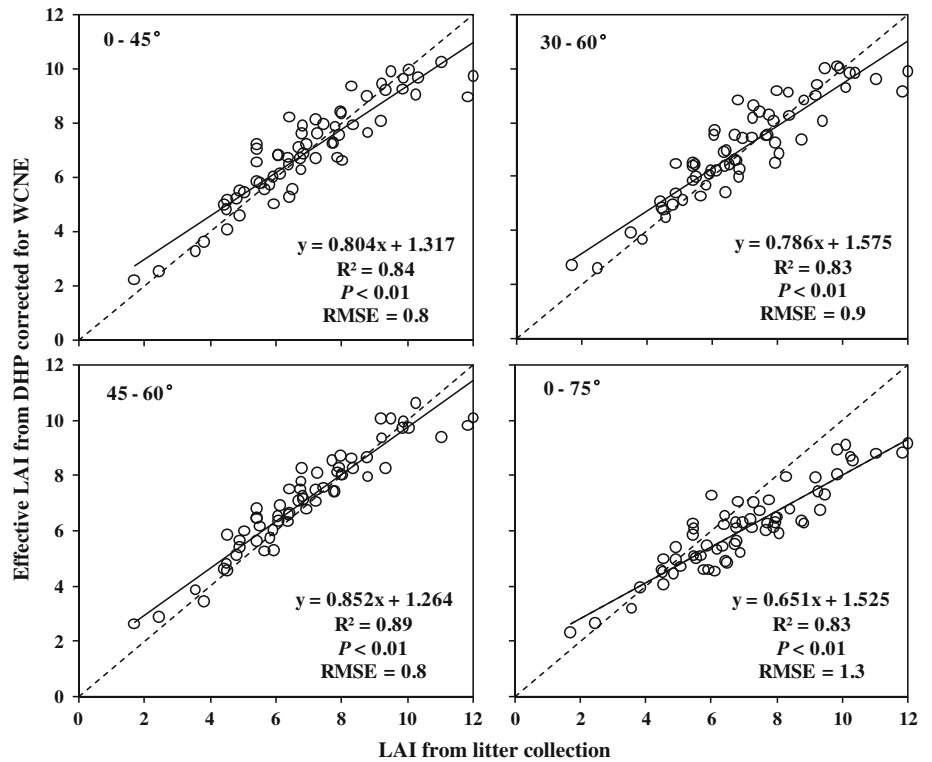


Fig. 7 Relationship between LAI estimated by litter collection (LAI_{lit}) and effective LAI from LAI-2000 with different zenith angle ranges. The dotted line indicates the 1:1 relationship

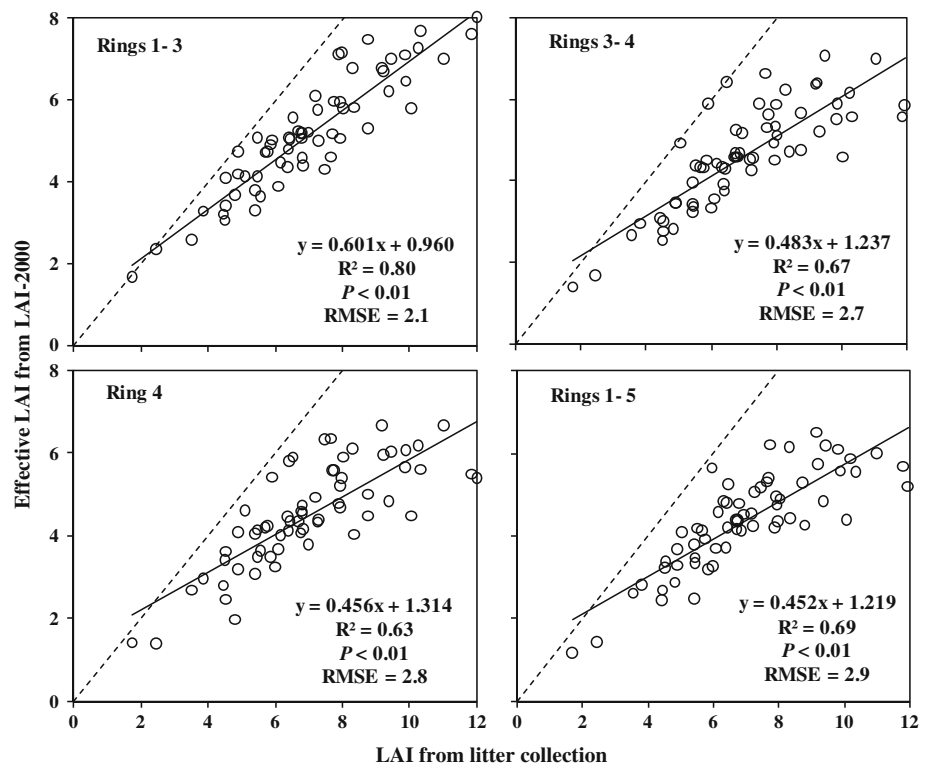
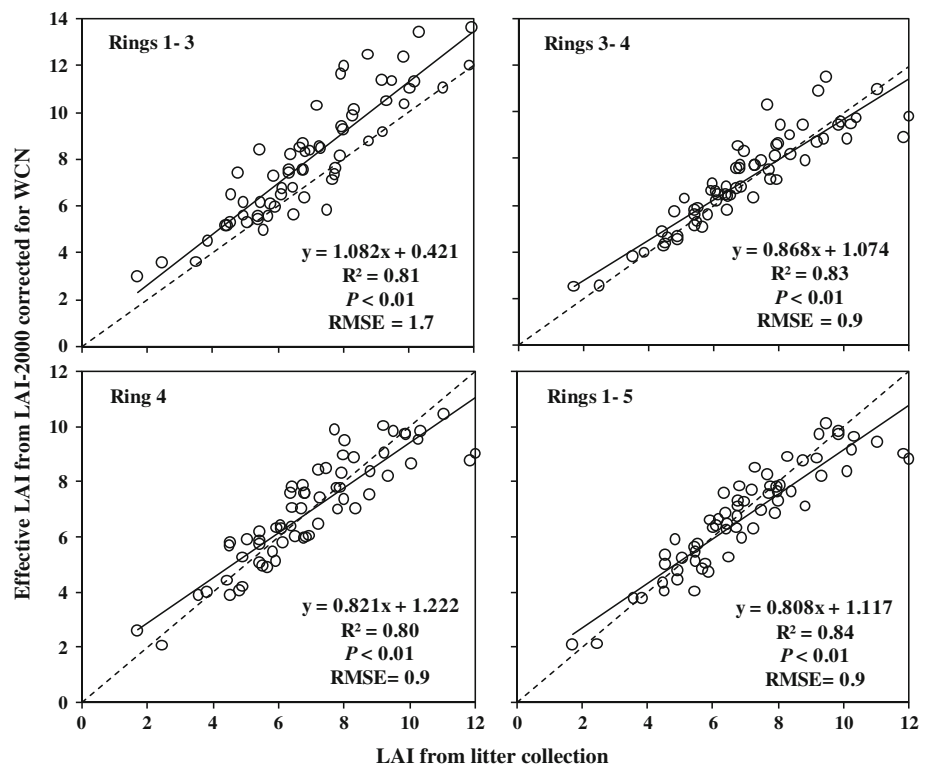


Fig. 8 Relationship between LAI estimated by litter collection (LAI_{lit}) and effective LAI from LAI-2000 after correcting for the woody-to-total area ratio (W), clumping index (C) and needle-to-shoot area ratio (N) ($LAI_{2000-WCN}$) according to Eq. (1) with different zenith angle ranges. The dotted line indicates the 1:1 relationship



L_e estimated from the LAI-2000 versus LAI estimated from the litter collection method (LAI_{lit})

Good correlations ($P < 0.01$) between LAI_{lit} and L_e from LAI-2000 were observed (Fig. 7), and R^2 and RMSE values were 0.82 and 2.1 based on rings 1–3, 0.67 and 2.7 based on rings 3–4, 0.63 and 2.8 based on ring 4, 0.69 and 2.9 based on rings 1–5, respectively. However, it can be seen that for all ranges, the slopes of LAI-2000 L_e against LAI_{lit} are less than 1, suggesting that the LAI-2000 instrument tends to generally underestimate LAI_{lit} in all ranges, by $25 \pm 10\%$ based on rings 1–3, $32 \pm 11\%$ based on rings 3–4, $34 \pm 12\%$ based on ring 4, and $36 \pm 10\%$ based on rings 1–5. On average, LAI-2000 L_e underestimated LAI_{lit} by an average of 32 %.

The correlation between LAI_{lit} and LAI-2000 L_e corrected for the woody-to-total area ratio, clumping index and needle-to-shoot area ratio ($LAI_{2000-WCN}$) remained highly significant ($P < 0.01$) (Fig. 8). It was enhanced, as proved by an increase of R^2 and a decrease of RMSE, with the values of 0.81 and 1.7 based on rings 1–3, 0.83 and 0.9 based on rings 3–4, 0.80 and 0.9 based on ring 4, and 0.84 and 0.9 based on rings 1–5, respectively (Fig. 8). The accuracy of LAI-2000 estimating LAI was improved with considering the above influence factors, the slopes of different zenith angle ranges were closer to the 1:1 line. The difference between LAI_{lit} and $LAI_{2000-WCN}$ was less than 6 % on average based on different zenith angle ranges, but it is worth noting that $LAI_{2000-WCN}$ overestimated LAI_{lit} by 17 % at rings 1–3. Meanwhile, the error caused by woody materials, the effect of clumping beyond and within the shoots was 42 % at rings 1–3, 36 % at rings 3–4, 35 % at ring 4, and 34 % at rings 1–5, with an average value of 37 %.

Discussion

Digital hemispherical photography (DHP) compared with LAI-2000

In our comparative study, DHP L_e tends to be smaller than LAI-2000 L_e at any zenith angle ranges, but they are significantly correlated (Table 5). Data processed with angle ranges close to the zenith (e.g., 0° – 45° , corresponding to rings 1–3) presented the largest difference between these two optical methods, probably because that range is more susceptible to exposure because of large gaps in the canopy or because of the effects of sunlit leaves viewed by the sensor for the DHP method. For DHP L_e , the largest difference among zenith angle ranges was 15 % between 45° – 60° and 0° – 75° . For LAI-2000 L_e , the largest difference was 15 % between rings 1–3 and 1–5, similar to the value

of 16 % averaged for six different forest sites (Chen et al. 2006), the range from 6 to 22 % for shrub canopies with different microtopography (Sonnentag et al. 2007), and 20 % in a forest at Howland (Richardson et al. 2011). In contrast to the LAI-2000, the DHP method underestimated L_e by an average of 43 %, but a significant relationship between them is found in any zenith angle ranges, especially for 45° – 60° or ring 4 ($r = 0.919$, $P < 0.01$). Similar results have been reported in the majority of the published studies in different forest types, e.g., DHP L_e underestimated LAI-2000 L_e by an average of 18 % in different forest stands (Frazer et al. 2000); DHP L_e underestimated LAI-2000 L_e by an average of 7.5 % in oak (*Quercus robur*)-beech (*Fagus sylvatica*) stand (Mussche et al. 2001). These differences were lower than our study, probably because different photograph exposure methods were used in their studies. In the present study, automatic exposure was used, and according to Zhang et al. (2005) and Chen et al. (2006), it caused over 40 % of underestimation relative to LAI-2000. We therefore depended on the relationship between DHP L_e obtained with automatic exposure and LAI-2000 L_e to eliminate the influence of error due to automatic exposure. After corrected, DHP L_e underestimated LAI-2000 L_e by an average of 4.5 % in our study site. Therefore, the accuracy of estimated LAI using the DHP method could probably be largely enhanced if a correct exposure is set in reference to the sky irradiance. Zhang et al. (2005) suggested that the correct exposure is to make the sky appear white by adding two stops of more exposure than the automatic exposure determined outside the canopy. The exposure determined this way is up to 4 stops smaller than the automatic exposure determined inside the canopy depending on the LAI. This means that if the automatic exposure inside the stand is used (as in our study), the photograph is over exposed by up to 4 stops, causing loss of leaves in the photo and a negative bias in the calculated LAI or L_e .

Reliability and utility of litter collection method

Recently, combining litter fall collection with leaf age can lead to accurate estimates of LAI in evergreen coniferous forests have been realized (Guiterman et al. 2012; Reich et al. 2012; Sprintsin et al. 2011). Therefore, the litter collection method could be useful not only in deciduous forests but also in coniferous or mixed broadleaf-coniferous forests (e.g., mixed broadleaved-Korean pine forest). Obviously, both SLAs of major species and the average leaf age of evergreen coniferous species should be known if the litter collection method is used in a mixed broadleaf-coniferous forest. The seasonality of the SLA of major species has been considered in this study, the coefficient of variation (i.e., the mean value is divided by the standard

deviation) of seasonal changes for all species ranged from 2 to 18 % (Table 1). It is unescapable to overestimate or underestimate LAI of a certain species if ignoring the seasonal changes of species-specific SLA. However, this uncertainty may not be as significant as expected in measuring LAI of a forest stand (except pure forest stand), especially with complex floristic composition. For instance, the uncertainty in estimating the LAI_{max} caused by the seasonal changes of SLA of all species was less than 2 % in this study site (i.e., an old-growth mixed broadleaved-Korean pine forest). The average leaf age for each evergreen coniferous species was measured with destructive sampling in the field. Additionally, the final average leaf age for each species was the weighted average of different tree classes (i.e., dominant, co-dominant and suppressed trees) based on their basal areas, not the arithmetic mean value of these classes. Based on our assessment, the total error of the litter collection method developed in our study was less than 5 % error, which is caused by the measurement of SLA and average leaf age or other uncertainty (e.g., the error from the electronic balance when measuring the weight of the litter fall).

In addition, LAI derived from optical methods (e.g., correcting LAI-2000 L_e using Eq. (1)) could be as accurate as those derived using direct methods (Chen 1996). In the present study, the average difference between LAI_{2000-WCN} and LAI_{lit} was less than 6 % based on different zenith angle ranges (Fig. 8), indicating that directly estimating LAI using the litter collection method in a mixed broadleaf-coniferous forest is feasible. From a practical standpoint, the litter collection method offers the advantage that it can work within non-destructive. However, this method is laborious in comparison to these optical methods, especially for collecting and sorting the litter fall termly. Therefore, evaluating the accuracy of these optical methods for estimating LAI in a mixed broadleaf-coniferous forest is very important, and the scheme of obtaining accurate LAI values based on these optical methods is urgent need.

Digital hemispherical photography (DHP) and LAI-2000 compared with the litter collection method

Optical methods normally lead to significant underestimation of LAI calculated by direct methods, as already pointed out by numerous authors (e.g., Thimonier et al. 2010; Küßner and Mosandl 2000; Jonckheere et al. 2004; Mason et al. 2012). Our average underestimation for DHP and LAI-2000 were 61 and 32 % relative to litter collection LAI, which were similar to 55 % observed by Jonckheere et al. (2005) and 30 % reported by Dufrêne and Bréda (1995) for these two methods, respectively. The underestimation increased with increasing LAI (Figs. 3, 7) as already reported

(Deblonde et al. 1994; Sampson and Allen 1995), probably due to the tendency for dense stands to concentrate the foliage in the upper part of the canopy (Cutini et al. 1998).

Woody materials and foliage clumping have been widely recognized as the largest error sources in LAI measurements by optical methods (Bréda 2003; Chen et al. 1997). In our study, the woody-to-total area ratio (α) had an average value of 3 % and a large variability (0.2–15.5 %), probably due to the spatial heterogeneity of the mixed broadleaved-Korean pine forest. Our α values are within the range of 3–41 % (Zou et al. 2009), and Fournier et al. (1996) suggested that the contribution of woody materials to LAI was less than 5 % in three coniferous forests. However, Chen et al. (1997), Cutini et al. (1998) and Barclay et al. (2000) found larger influences of woody materials on optical estimates of LAI at their test sites. No measurement of the woody-to-total area ratio is reported in the literature for mixed broadleaf-coniferous stands. For coniferous species, both beyond shoot clumping (Ω_E) and within shoot clumping (γ_E) exist (Chen et al. 1997). We obtained Ω_E with an average value of 0.90, which is in general agreement with results at different forest sites in Canada reported by Chen et al. (2006). The γ_E of *Pinus koraiensis* was larger than those of the other two coniferous species, probably because of its shoot morphology with five needles grouped in a bundle, making needles in a shoot denser. Moreover, the stand-level γ_E value of each sample point was determined according to the basal area percentages of all species within a certain area (20 m × 20 m, as centered on each sample point). Our average γ_E value (1.43) for the stand is similar to the one (1.41) reported by Chen (1996) for six black spruce (*Picea mariana*) and jack pine (*Pinus banksiana*) stands, and still within the range of 1.2–2.0 for coniferous species (Kucharik et al. 1998).

The difference in L_e between optical methods (DHP and LAI-2000) after correcting for the above three parameters (α , Ω_E and γ_E) and LAI_{lit} decreased (Figs. 4, 8) markedly from the case without making these corrections. The total error in α , Ω_E and γ_E was found to be 21 and 37 % using DHP and LAI-2000 methods, respectively, similar to the value of 10–30 % reported by Chen et al. (1997). In this case, the sum of errors caused by these parameters differs between optical methods, probably due to different errors in L_e measurement.

In contrast to LAI-2000, the accuracy of the DHP LAI measurement still depends on correct exposure setting, which is gaining more attention (Beckschäfer et al. 2013; Chen et al. 2006; Song et al. 2014; Zhang et al. 2005). However, DHP L_e after only correcting for the incorrect (e.g., automatic) exposure still underestimated LAI_{lit} by an average of 37 %, indicating the importance of considering the influence of α , Ω_E and γ_E in order to ensure the LAI measurement accuracy of DHP is over 95 %.

Conclusions

We directly measured LAI in a mixed broadleaf-coniferous forest using the litter collection method, and used this measurement to validate two conventional indirect optical methods (DHP and LAI-2000). LAI derived from the litter collection method was significantly correlated with optical estimates from DHP and LAI-2000. However, L_e from these two optical methods based on different zenith angles underestimated LAI on average by 61 and 32 %, respectively. The sources of error derived from the optical methods were summarized, including woody materials, clumping effect beyond and within shoots, selection of zenith angles, photograph exposure setting for the DHP method. For the DHP method, the accuracy of L_e was improved by 21 % after considering woody-to-total area ratio (α), clumping index (Ω_E) and needle-to-shoot area ratio (γ_E) and was further improved by 36 % after correcting for the error due to exposure, and 45° – 60° was the optimal zenith angle range. For the LAI-2000 method, L_e was improved by 37 % after considering the influence of α , Ω_E and γ_E , and the rings 1–3 was the optimal zenith angle range. Finally, the differences between DHP or LAI-2000 LAI and litter collection LAI were all less than 6 %, suggesting that with careful operation of optical instruments and data processing, the optical LAI can be as reliable as the direct measurement. The good agreement between LAI estimates using the litter collection and optical methods also suggests that combining litter fall collection with leaf age of coniferous species could be a practical and reliable method for measuring LAI in a mixed broadleaf-coniferous forest.

Author contribution statement Conceived and designed the experiments: Guangze Jin. Performed the experiments: Zhili Liu, Yujiao Qi. Analyzed the data: Zhili Liu, Yujiao Qi. Wrote the paper: Zhili Liu, Jing M. Chen, Guangze Jin.

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Conflict of interest The authors declare that they have no conflict of interest.

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