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Evaluation and correction of optically derived leaf area index in different temperate forests

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In recent years optical techniques for rapid LAI measurements have been developed, but few studies have been performed to evaluate the accuracy of optical estimation of LAI in mixed deciduous-evergreen forest stands. In this paper, we assessed the accuracy of digital hemispherical photography (DHP) and the LAI-2000 for the estimation of effective LAI (L_e) by comparison with litter collection LAI (LAI_{lit}) in four mixed deciduous broadleaf and evergreen needleleaf forests and one deciduous needleleaf forest. We also evaluated the relative contribution of major error sources to the determination of LAI by optical methods, including the woody-to-total area ratio (α), the element clumping index (Ω_E) and the needle-to-shoot area ratio (γ_E). Additionally, incorrect automatic photographic exposure has been considered for DHP. DHP L_e underestimated LAI_{lit} by an average of 44-70% in different forests, and the difference between LAI_{lit} and DHP L_e after correction for the automatic exposure, α, Ω_E and γ_E ranged from 1% to 21% in five forest stands. In contrast, LAI values from LAI-2000 were more similar to the direct litter collection LAI. The LAI-2000 L_e underestimated LAI_{lit} by an average of 13-40% in these forests, while the accuracy of the best estimates of LAI using LAI-2000 methods is over 93% after considering α, Ω_E and γ_E. The error caused by automatic exposure to DHP L_e is larger than other factors in all forest stands, and the γ_E was the main uncertainty to LAI-2000 L_e in most forest stands. Moreover, optical LAI (both DHP and LAI-2000) was significantly ($P < 0.01$) correlated with LAI_{lit}, especially the corrected LAI obtained by the LAI-2000 ($R^2 = 0.83$, RMSE = 1.04). Our results demonstrate that the above factors affect the estimation of LAI by optical methods, thus the species composition of a forest stand should be seriously considered in order to improve the accuracy of LAI by optical methods.

Keywords: Leaf Area Index (LAI), Digital Hemispherical Photography (DHP), LAI-2000, Woody Materials, Clumping Effects, Automatic Exposure, Litter Collection, Correlation

Introduction

The leaf area index (LAI), which is defined as half the total green leaf area per unit ground surface area (Chen & Black 1992), is an important canopy parameter required for many physiological and ecosystem studies (Macfarlane et al. 2007, Bequet et al. 2012, Beckschäfer et al. 2013). For instance, an accurate LAI estimation is essential for modeling light and precipitation interception, CO_2 fluxes, evapotranspiration, and dry deposition (Jonckheere et al. 2005, Beckschäfer et al. 2014, Gonsamo & Chen 2014, Zhao et al. 2014). In addition, LAI is commonly used to compare canopy development or structure over time or under different environmental conditions or disturbances (Martens et al. 1993). Therefore, accurately estimating the LAI is of great interest, especially in tall forest systems.

Recently, direct and indirect methods have been recommended to estimate the LAI in a forest stand. Destructive sampling, allometry, and litter collection are the most commonly used direct methods (Chen et al. 1997, Bréda 2003, Jonckheere et al. 2004). Although the LAI value obtained is similar to the true values, such direct methods are time consuming and labor intensive, and especially destructive for the former two methods. In contrast, the litter collection method is the best choice for obtaining an accurate LAI in a forest stand, especially in protected areas. This method has traditionally been used to estimate the LAI in a deciduous forest that has a single leaf-fall season (Neumann et al. 1989, Cutini et al. 1998, Eriksson et al. 2005, Ishihara & Hiura 2011). Recently, the annual maximum LAI of evergreen conifer forests with continuous leaf fall over years has been obtained by combining the annual litter fall values with the average life span of evergreen needles (Sprintsin et al. 2011, Guiterman et al. 2012, Reich et al. 2012). However, litter collection is more laborious in comparison to indirect methods, especially for collecting and sorting the litter fall termly.

Indirect inference of LAI is based on the gap fraction or gap size distribution within a canopy using radiative transfer theories (Ross 1981). Therein, digital hemispherical photography (DHP) and LAI-2000 plant canopy analyzer are the most widely used techniques for simultaneous measure-

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ments of the canopy structural characteristics from several zenith angles. However, the accuracy of the LAI from optical methods has typically been assessed using direct estimation of the LAI because the woody materials and foliage clumping effects (including 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, Chianucci et al. 2014, Lopes et al. 2014). For this reason, the effective LAI (L_e) has been proposed to describe optically derived LAI estimates in the literature (Chen & Black 1992). Additionally, recent studies reported that an incorrect exposure setting in DHP LAI estimation may be a significant source of error (Chen et al. 1991, Cescatti 2007, Chianucci & Cutini 2012, Beckschäfer et al. 2013, Song et al. 2013) by decreasing the contrast between the sky and foliage, further affecting the calculation of the LAI by DHP. Comparisons of the LAI estimated from DHP and the LAI-2000 techniques with those obtained from direct measurements have often been reported (Dufrêne & Bréda 1995, Chen et al. 1997, Thimonier et al. 2010, Mason et al. 2012, Olivas et al. 2013). However, the accuracy of the L_e from DHP or LAI-2000 after correction for woody materials and clumping effects has rarely been evaluated based on non-destructive direct methods in different mixed deciduous-evergreen (*i.e.*, deciduous broadleaf and evergreen needleleaf) and deciduous needleleaf forest stands.

In the present study, we directly estimated the LAI using a litter collection method in five different temperate forest stands in China, and these directly measured LAI values were used as a basis for validating optical measurements of LAI in the same sites. Our specific objectives were: (1) to evaluate the accuracy of the L_e derived from the DHP and LAI-2000 methods in different forest stands; (2) to quantify the relative contributions of different sources of errors (*e.g.*, woody materials, clumping effects within a canopy or automatic exposure) to LAI estimates by optical methods; and (3) to develop correlations between the optically determined L_e and the litter collection LAI, and examine whether these relationships are improved after considering the other canopy structural factors (*e.g.*, woody materials and the clumping effects within a canopy) in estimating the LAI using the optical methods.

Materials and methods

Study site

The study site is in the Liangshui National Nature Reserve, in northeastern China (47° 10′ 50″ N, 128° 53′ 20″ E). The site is characterized by a rolling mountainous terrain, ranging from 300 to 707.4 m a.s.l. with a typical slope of 10°-15°. The mean annual air temperature is -0.3 °C, and the mean annual rainfall is 676 mm. The area has a long history of community development with a variety of forest stands. These forests mainly include mixed broadleaved-Korean pine (*Pinus koraiensis*) forest (BK), selection cutting forest (SC), secondary birch (*Betula platyphylla*) forest (SB), Korean pine plantation (KP) and Dahurian larch (*Larix gmelinii*) plantation (DL). SC is derived from the Korean pine, where large DBH were cut in the BK that grew originally approximately 35 years ago; SB, KP and DL are forests developed on the harvested sites where BK grew originally. Specific information about the forest stands in this study is summarized in Tab. 1.

Both BK and SB had one sampling plot (60 × 60 m). SC, KP and DL all had three sampling plots (20 × 30 m). Twenty litter traps were set randomly in both BK and SB plots. For SC, KP and DL, each plot was divided into 10 × 10 m subplots, and 6 litter traps were separately installed at the center of each subplot (*i.e.*, a total of 18 litter traps for each forest stand). Each litter trap had a 0.5 or 1.0 m² square aperture, and its base was approximately 0.5 m above the ground.

Tab. 1 - General status and species composition of the five forest stands under investigation in China.

Forest stands	Major species	Density (trees ha⁻¹)	Mean DBH (cm)	Basal area (m² ha⁻¹)	Land-use history	Age (year)
Mixed broad-leaf-Korean pine forest	*Pinus koraiensis, Acer mono, Tilia amurensis, Betula costata*	2373	7.4	42.3	Virgin forest	>300
Selection cutting forest	*Pinus koraiensis, Betula costata, Fraxinus mandshurica, Ulmus japonica*	2010	8.7	26.9	Selection cutting in virgin forest in 1980 ca.	35
Secondary birch forest	*Betula platyphylla, Larix gmelinii, Picea* spp.	2854	7.2	23	Regeneration forest after clear cutting in 1953	61
Korean pine plantation	*Pinus koraiensis, Betula platyphylla, Larix gmelinii*	1973	11.5	33.3	Afforestation in 1954	60
Dahurian larch plantation	*Larix gmelinii, Fraxinus mandshurica, Acer mono*	1506	8.6	30.2	Afforestation in 1954	60

Litter collection leaf area index

Litterfall was collected monthly in each plot in 2013. Data collected in fall-winter were used for calculation of LAI in deciduous species, while data collected annually were used for calculation of LAI in evergreen species. In addition, we assumed that the new LAI for evergreen species is the same each year, a measurement of LAI in any year representing the average condition. Therefore, the LAI of evergreen species was obtained from multiplying the LAI from the litterfall within a certain period (one year) by the average life span of each species. The measurement of LAI at the plot was then obtained by summing such LAIs for all the major species.

SLA for major species and the average life span for evergreen species were essential for estimating LAI using litter collection. In the present study, the SLA for major species was measured once a month from August to November in 2012. The experimental details and SLA values reported by Liu et al. (2014), and the mean SLA values over different periods were used to estimate LAI for major species in the litter collection method. It is worth noting that SLA can change along with falling of the leaves, thus the SLAs for major species were corrected using a shrinkage coefficient (ranging from 3.5 to 8.0%) estimated from a sub-sample of green leaves collected in the study forest plots. Potential interannual variability in the SLA was considered negligible. The average life span for *Pinus koraiensis, Abies nephrolepis* and *Picea* spp. was 3.07, 3.69 and 3.91 years, respectively (Liu et al. 2014).

Optical leaf area index

The effective LAI, L_e can be usually measured using a DHP technique and LAI-2000 instruments based on the Miller (1967) theory (Chen 1996 – eqn. 1):

$$L_e = 2\int_0^{\pi/2} \ln\left[\frac{1}{P(\theta)}\cos\theta\sin\theta\, d\theta\right]$$

where $P(\theta)$ is the measured canopy gap fraction at the zenith angle θ, which is the best when averaged over the entire azimuthal angle range.

DHP measurements

All hemispherical photographs were collected using a digital camera (Coolpix 4500, Nikon, Tokyo, Japan), with a 180° fisheye lens (Nikon FC-E8) in mid-July 2013. The camera was held 1.3 m above the ground using a tripod. All of the photographs were taken under an evenly overcast sky. We chose the following settings for the camera: (1) aperture priority mode with aperture set at F 5.3 (*i.e.*, automatic exposure); (2) high image quality (2272 × 1704 pixels); and (3) fine JPEG format. The photographs were processed with the DHP software to derive the L_e (Leblanc et al. 2005). A circular photograph was divided into concentric 6 rings spanning the zenith angle range from 0° to 90° (*i.e.*, ring 1: 0°-15°; ring 2: 15°-30°; ring 3: 30°-45°; ring 4: 45°-60°; ring 5: 60°-75°; ring 6: 75°-90°), but according to LAI-2000 measurements, 0°-75° (*i.e.*, 1-5 rings) zenith angle ranges was selected to derive L_e and the Gamma function was set to 1 (Chianucci & Cutini 2012).

LAI-2000 measurements

Canopy gap fraction and L_e were also estimated with LAI-2000 measurements (Licor Inc., Lincoln, NE, USA) at five concentric rings (ring 1: 0°-13°; ring 2: 16°-28°; ring 3: 32°-43°; ring 4: 47°-58°; ring 5: 61°-74°), with the same time and location as hemispherical photographs. A LAI-2000 unit was subsequently operated 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. The LAI-2000 data were processed using the available C2000 software for L_e within all five rings.

Correction of optical LAI estimates

The error of optical estimated LAI caused by woody materials and clumping effects within canopies has often been realized (Chen et al. 1997, Ryu et al. 2010, Chianucci & Cutini 2012). Therefore, the following parameters should be considered in order to obtain a more accurate LAI (denoted as L) based on L_e (Chen et al. 1997 – eqn. 2):

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

where α is the woody-to-total area ratio representing the woody materials (quantified by the woody area index, WAI) contribution to L_e; L_e is the effective LAI from optical instruments (DHP or LAI-2000); Ω_E is the clumping index quantifying the effect of foliage clumping at scales larger than shoots; and γ_E is the needle-to-shoot area ratio quantifying the effect of foliage clumping within shoots. For broadleaf species, individual leaves are considered foliage elements, thus γ_E = 1.0, but for needleleaf species, γ_E is usually larger than 1.0. The caveat of these parameters (*i.e.*, α, Ω_E and γ_E) in eqn. 2 were measured only once, *i.e.*, the same parameters were used to correct L_e derived from both DHP and LAI-2000.

Woody-to-total area ratio (α)

In this study we measured the α value using the Adobe Photoshop® (PS) software package (Qi et al. 2013). For mixed deciduous-evergreen forest stands (*i.e.*, BK, SC, SB and KP), we first obtained the L_e of a photograph using the DHP software. Second, we replaced the green materials (mainly leaves and needles) with sky through the "Clone Stamp Tool" of PS, leaving only woody materials visible (mainly stems) on the image. We could then obtain the WAI of the photograph by DHP with the same threshold as above. Finally, the parameter α was then derived accordingly ($\alpha = WAI/L_e$) in mixed deciduous-evergreen forest stands. For the deciduous forest stand (DL), we used a background method to remove the influence of woody materials on the optical estimation of LAI. Generally, the WAI is the summation of stem area index (SAI) and branch area index (BAI). In this study, we ignored the contribution of the BAI to the LAI. First, we collected photographs at each sample point in DL during a leafless period (May 1st). Second, we separated the stems from woody materials using the "Clone Stamp Tool" in PS, similar to the process in mixed deciduous-evergreen forests, replacing the branches with sky. Finally, we obtained the α value for DL. It is worth noting that using the above procedure the WAI only represents the stem area index.

Element clumping index (Ω$_E$)

The Ω_E was computed based on the gap size and fraction analysis (Chen & Cihlar 1995, Leblanc et al. 2005 – eqn. 3):

$$\Omega_E(\theta)=\frac{\ln[F_m(0,\theta)][1-F_{mr}(0,\theta)]}{\ln[F_{mr}(0,\theta)][1-F_m(0,\theta)]}$$

where $F_m(0,\theta)$ is the measured accumulated gap fraction larger than zero (*i.e.*, the canopy gap fraction), and $F_{mr}(0,\theta)$ is the gap fraction for the canopy when large gaps that are not theoretically possible in a random canopy have been removed for a given LAI and foliage element width. The advantage of this method to derive Ω_E is that it can be applied to all types of plant canopies without the need for spatial pattern assumptions about canopy elements (Gonsamo & Pellikka 2009). The Ω_E values were measured by DHP-TRAC software (Chen et al. 2006, Macfarlane et al. 2007) within the zenith angle range 0-75°.

Needle-to-shoot area ratio (γ$_E$)

The γ_E for the four needleleaf species (*Pinus koraiensis, Abies nephrolepis, Picea* spp. and *Larix gmelinii*) in the five forest stands was quantified using destructive sampling in the field. For each needleleaf 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). Samples were collected at three heights for each tree: 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 the implementation details are reported in Liu et al. (2012). Finally, the γ_E in a plot was obtained by weighting the γ_E of the trees of different species (both broadleaf and needleleaf species) by their relative contribution to the total basal area in the plot.

In comparison to the LAI-2000 instrument, the accuracy of LAI measured using DHP is affected by the additional issue of photograph exposure setting. Therefore, we additionally corrected a systematic error in the DHP method due to incorrect automatic exposure (defined as E), based on the relationship between the DHP L_e obtained by automatic exposure and LAI-2000 L_e reported by Zhang et al. (2005), *i.e.*, $y = 0.5611 \cdot x + 0.3586$ ($R^2 = 0.77$), where x is the L_e estimated by LAI-2000, and y is the L_e estimated by DHP within automatic exposure.

Bias analysis

For the DHP method, the sources of bias of LAI measurement were caused by α, Ω_E, γ_E, and E, thus, LAI = $f_{DHP}(\alpha, \Omega_E, \gamma_E, E)$. Then, we calculated the total bias (ΔLAI – eqn. 4):

$$\Delta LAI=\frac{\partial LAI}{\partial\alpha}\Delta\alpha+\frac{\partial LAI}{\partial\Omega_E}\Delta\Omega_E+\frac{\partial LAI}{\partial\gamma_E}\Delta\gamma_E+\frac{\partial LAI}{\partial E}\Delta E$$

where $\Delta\alpha = 0-\alpha$, $\Delta\Omega_E = 1-\Omega_E$, $\Delta\gamma_E = 1-\gamma_E$ and $\Delta E=1-E$. For the LAI-2000 method, the sources of bias of LAI measurement were caused by α, Ω_E, and γ_E, thus, LAI = $f_{LAI\text{-}2000}(\alpha, \Omega_E, \gamma_E)$. Then we calculated the total bias (eqn. 5):

$$\Delta LAI=\frac{\partial LAI}{\partial\alpha}\Delta\alpha+\frac{\partial LAI}{\partial\Omega_E}\Delta\Omega_E+\frac{\partial LAI}{\partial\gamma_E}\Delta\gamma_E$$

Therein the calculation of $\Delta\alpha$, $\Delta\Omega_E$ and $\Delta\gamma_E$ were the same as in eqn. 4.

Results

Gap fraction estimation by optical methods

Generally, gap fraction measured by both DHP and LAI-2000 decreased with increasing zenith angle in different forest stands (Fig. 1), although DHP gave larger gap fraction values than that of LAI-2000, probably because of the incorrect automatic exposure set in DHP.

Parameters for correcting optical LAI

All parameters required for LAI correction using eqn. 2 are summarized in Tab. 2. The woody-to-total area ratio (α) ranged from 3% to 8% in five forest stands. The clumping effects beyond shoots (Ω_E) varied slightly with the forest stand; the largest Ω_E was 0.92 in DL, and KP had the smallest Ω_E with a value of 0.89. The KP had the largest clumping effects within the shoots (γ_E) with a value of 1.46. The γ_E for SB (with a value of 1.08) was lower than that obtained for the other four forest types, because the large proportion of broadleaf species increased the weight of γ_E for these species (γ_E = 1.0) in the overall γ_E calculated for the whole forest stand.

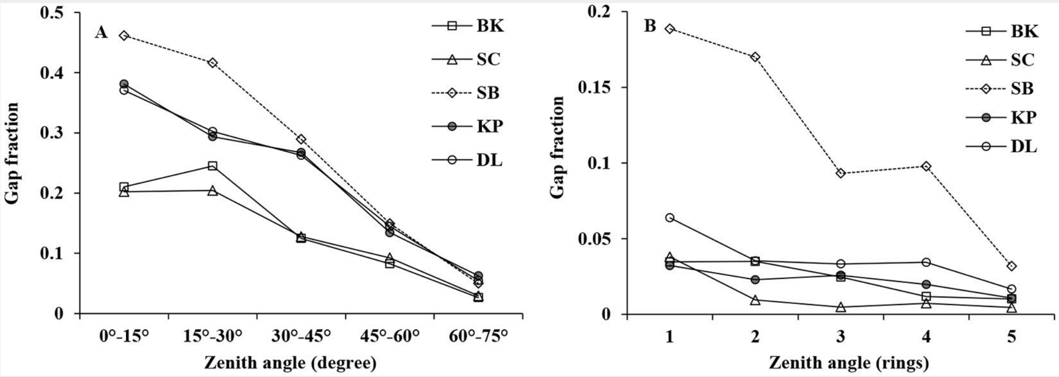


Fig. 1 - Gap fraction comparison among DHP (A) and LAI-2000 (B) in five forest stands.

Tab. 2 - Correction factors for woody-to-total area ratio (α), clumping index (Ω_E) and needle-to-shoot area ratio (γ_E) on optical LAI in five forest stands. (BK): mixed broadleaved-Korean pine forest; (SC): selection cutting forest; (SB): secondary birch forest; (KP): Korean pine plantation; (DL): Dahurian larch plantation.

Factors	BK	SC	SB	KP	DL
α (%)	4	3	5	5	8
Ω_E	0.90	0.91	0.91	0.89	0.92
γ_E	1.41	1.28	1.08	1.46	1.27

Tab. 3 - Comparison of the LAI from litter collection and optical (DHP and LAI-2000) methods in five forest stands. Means ± standard deviations are reported. (LAI_{lit}): LAI from litter collection; (DHP L_e): effective LAI derived from the DHP method; ($LAI_{DHP\text{-}C}$): DHP L_e after correction for automatic exposure, woody materials and clumping effects within canopies; (LAI-2000 L_e): effective LAI derived from the LAI-2000 method; ($LAI_{2000\text{-}C}$): represents LAI-2000 L_e after correction for woody materials and clumping effects within canopies.

Forest Type	LAI_{lit}	DHP L_e	$LAI_{DHP\text{-}C}$	LAI-2000 L_e	$LAI_{2000\text{-}C}$
BK	8.84 ± 1.04	3.05 ± 0.18	8.81 ± 0.78	5.28 ± 0.85	8.33 ± 1.35
SC	9.42 ± 0.66	2.99 ± 0.36	6.82 ± 0.83	6.82 ± 0.77	9.31 ± 1.05
SB	3.69 ± 0.48	1.96 ± 0.12	3.47 ± 0.21	3.11 ± 0.41	3.57 ± 0.48
KP	7.95 ± 1.07	2.33 ± 0.19	6.09 ± 0.50	5.12 ± 1.04	8.56 ± 1.11
DL	5.59 ± 1.13	2.21 ± 0.29	4.69 ± 0.70	4.23 ± 1.43	5.43 ± 1.03

Comparison of the LAI from direct and indirect methods

Based on the litter collection, the SC had the largest LAI, with a value of 9.42 ± 0.66 (SD), followed by BK, KP, DL and SB, with values of 8.84 ± 1.04, 7.95 ± 1.07, 5.59 ± 1.13 and 3.69 ± 0.48, respectively (Tab. 3). Generally, the optical LAI (both DHP L_e and LAI-2000 L_e) underestimated the LAI_{lit} for each forest stand (Tab. 3, Fig. 2). DHP L_e underestimated LAI_{lit} by an average of 65%, 68%, 44%, 70% and 59% for BK, SC, SB, KP and DL, respectively, indicating that the difference between DHP L_e and LAI_{lit} are affected by the species composition of forest stands. However, the accuracy of DHP L_e after correcting for the woody materials, clumping effects within canopies and incorrect exposure was greatly improved in all forest stands. The difference between the LAI_{lit} and the corrected LAI from DHP was 1%, 2% and 12% in BK, SB and DL, respectively (Tab. 3, Fig. 2). However, the corrected LAI from DHP still underestimated LAI_{lit} by 17% and 21% on average for SC and KP, respectively. In contrast, LAI-2000 L_e underestimated LAI_{lit} by 40%, 27%, 13%, 36% and 21% on average for BK, SC, SB, KP and DL, respectively. The accuracy of the LAI-2000 L_e after correction for woody materials and clumping effects within canopies markedly improved in all five forest stands. The difference between the LAI_{lit} and corrected LAI from LAI-2000 was less than 7% in all forest stands (Fig. 2), indicating that the correction scheme for LAI-2000 is reasonable and effective not only in deciduous but also mixed deciduous-evergreen forest stands. It is worth noting that the corrected LAI from the optical method showed larger LAI values than LAI_{lit} in some forest stands. After correcting LAI from DHP, average overestimation was only 1% for BK, while it was lower than 7% for SB, KP and DL after correcting LAI from LAI-2000, based on comparison with LAI_{lit}.

Overall, the bias due to each factor varied with forest stands more than optical mea-

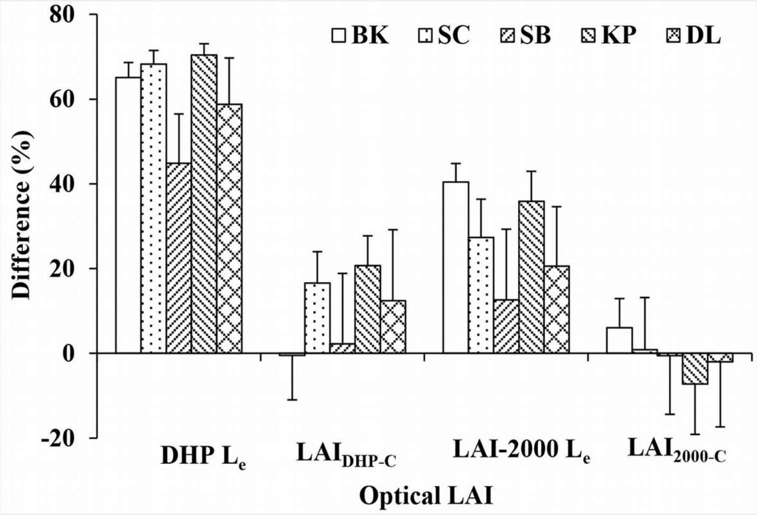
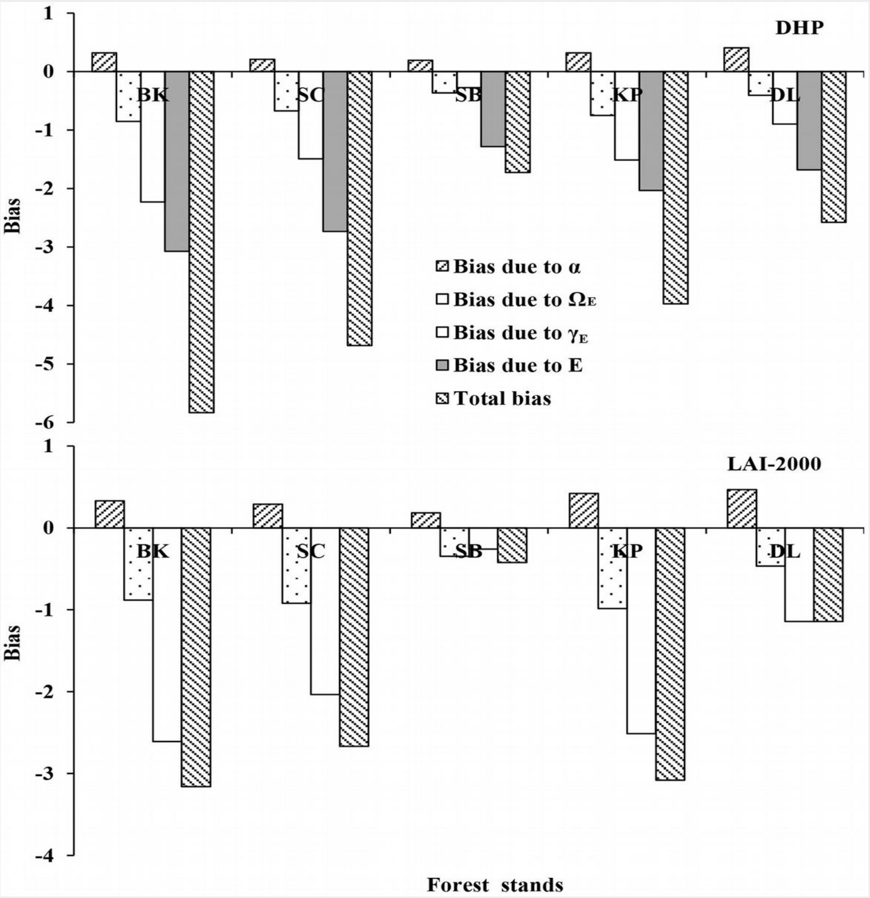


Fig. 2 - Differences between litter collection LAI and optical LAI (DHP and LAI-2000). All abbreviations are the same as in Tab. 2. Difference (%) = (LAI_{lit} optical LAI)/ LAI_{lit} ×100. Optical LAI includes the effective and corrected LAI from DHP and LAI-2000.

Fig. 3 - The biases caused by woody-to-total area ratio (α), clumping index (Ω_E), needle-to-shoot area ratio (γ_E) or automatic exposure (E) for optical LAI (DHP and LAI-2000) in five different forest stands.



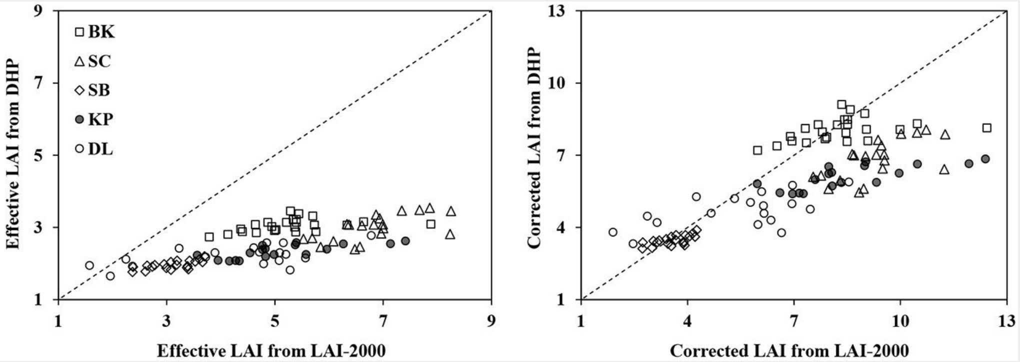
Tab. 4 - Correlation between litter collection LAI (LAI_{lit}) and optical LAI (DHP and LAI-2000). The expression used for regressions was $y = ax + b$. Coefficients of determination (R^2), root mean squared errors (RMSE) and probability (P) of the regressions were reported. (*): regressions in which the intercept does not differ from zero and the slope does not differ from 1 (p <0.05). All abbreviations in LAI formats are defined in Tab. 2.

LAI formats (*x vs.y*)	a	b	R^2	RMSE	P
LAI-2000 L_e *vs.* DHP L_e	0.25	1.32	0.57	0.33	< 0.01
Corrected LAI from LAI-2000 *vs.* Corrected LAI from DHP	0.56*	1.99	0.66	1.02	< 0.01
LAI from litter collection *vs.* DHP L_e	0.18	1.23	0.79	0.23	< 0.01
LAI from litter collection *vs.* Corrected LAI from DHP	0.69*	1.05*	0.76	0.98	< 0.01
LAI from litter collection *vs.* LAI-2000 L_e	0.52*	1.07*	0.75	0.76	< 0.01
LAI from litter collection *vs.* Corrected LAI from LAI-2000	0.90*	0.81*	0.83	1.04	< 0.01

surement (*i.e.*, DHP and LAI-2000), and the contribution of α to optical L_e was opposite with other factors (*e.g.*, Ω_E, γ_E or E - Fig. 3). For DHP L_e, the absolute bias due to automatic exposure was largest in different forests, followed by that due to γ_E. The total bias of DHP L_e due to all factors were -5.83, -4.69, -1.72, -3.97, and -2.58 for BK, SC, SB, KP, and DL, respectively. In contrast, for LAI-2000 L_e, the absolute bias due to γ_E was larger than those due to α and Ω_E in most stands (except SB). For BK, SC, and KP, the absolute biases of LAI-2000 L_e due to Ω_E were larger than that of α, but for SB and DL, the biases of these factors showed different patterns. The total bias of LAI-2000 L_e due to all factors were -3.16, -2.66, -0.42, -3.08, and -1.14 for BK, SC, SB, KP, and DL, respectively.

Generally, the DHP method gave smaller L_e values than those obtained by LAI-2000 in all forest stand (Tab. 3, Fig. 4). DHP L_e underestimated LAI-2000 L_e by an average of 42%, 56%, 37%, 54% and 48% for BK, SC, SB, KP and DL, respectively. However, the DHP L_e significantly correlated with LAI-2000 L_e ($R^2 = 0.57$, RMSE = 0.33 and $P < 0.01$ - Tab. 4). The correlation between DHP L_e and LAI-2000 L_e was enhanced after correcting for the parameters in eqn. 2 (Fig. 4), as indicated by the increased R^2 value (0.66 -

Fig. 4 - Scatter analysis of the LAI estimated by the LAI-2000 and DHP methods in five forest stands. The dotted line represents the 1:1 relationship.



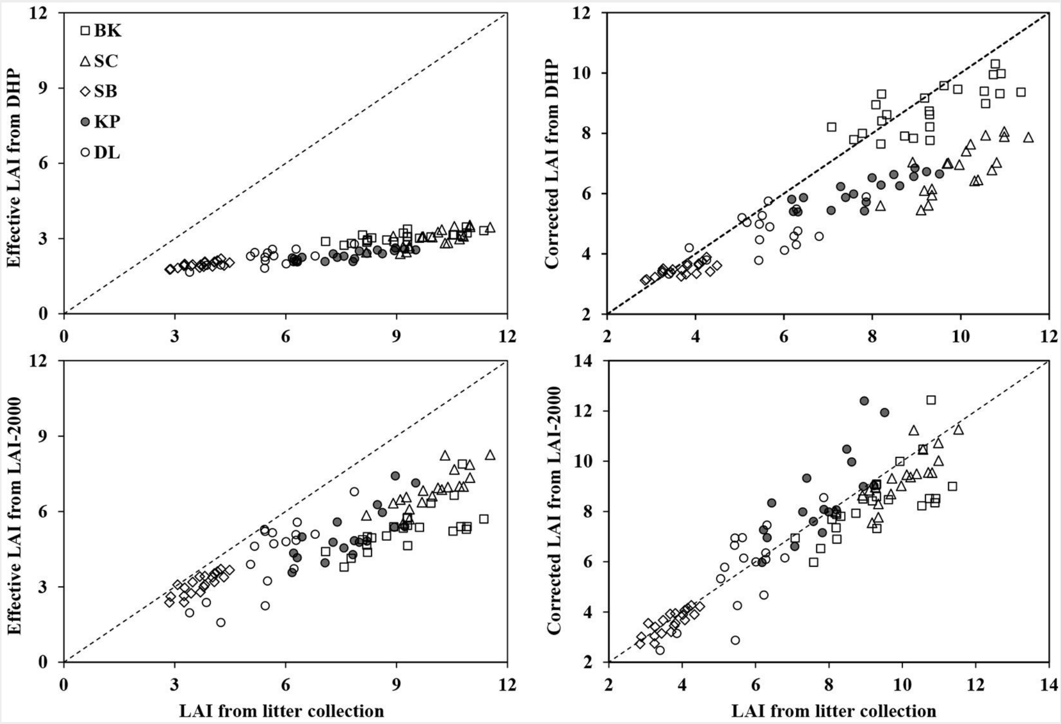


Fig. 5 - Scatter analysis of the LAI estimated by litter collection and optical methods (DHP and LAI-2000) in five forest stands. Optical LAI includes effective and corrected LAI from DHP and LAI-2000. The dotted line indicates the 1:1 relationship.

Tab. 4).

Fig. 5 illustrates the correlation between LAI_{lit} and LAI from optical methods (both DHP and LAI-2000) in five different forest stands. A significant correlation ($P < 0.01$) between the LAI_{lit} and uncorrected L_e obtained by optical methods was observed (Tab. 4), with $R^2 = 0.79$ and 0.75, RMSE = 0.23 and 0.76 for DHP and LAI-2000, respectively. For DHP L_e, the correction for woody materials, clumping effects and incorrect exposure setting did not improved the correlation with LAI_{lit} clearly. In contrast, the correction scheme on LAI-2000 was more effective, as indicated by the R^2 value of 0.83. These results suggested that the error caused by woody materials and clumping effects within canopies (additional incorrect exposure for DHP) explained the majority of the error caused by estimating LAI by optical methods (*e.g.*, DHP and LAI-2000).

Discussion

In this study optical methods (*e.g.*, DHP and LAI-2000) gave lower LAI values than the litter collection method in different forest stands. DHP L_e underestimated LAI_{lit} by 44-70%, while underestimation ranged from 13% to 40% for LAI-2000 in these forest stands. Similar results have often been reported in previous studies. Jonckheere et al. (2005) reported that the LAI-2000 underestimated the directly estimated LAI by 52%, and the underestimation for hemispherical photographs averaged 55%. Mason et al. (2012) found that the LAI-2000 L_e underestimated destructive sampling LAI in the range 30% to 60% in *Pinus radiata* plantations in New Zealand. Van Gardingen et al. (1999) found the DHP L_e underestimated the LAI by 50% relative to the harvesting method in a canopy of *Gliricidia sepium* in Mexico. However, we found a significant correlation between directly measured LAI and optical LAI in different forest stands (Tab. 4, Fig. 5). Similar relationships have been reported in the majority of published studies in different forest stands, *e.g.*, Cutini et al. (1998) in stands of the main broad-leaved forest species, Sonnentag et al. (2007) in shrubs, Mason et al. (2012) in *Pinus radiata* plantations and Chianucci & Cutini (2013) in different deciduous forests.

The error in the estimation of LAI by optical techniques was mainly caused by woody materials and clumping effects within canopies. However, correcting for the clumping effects results in higher LAI values than the L_e values alone, while correcting for the woody materials only gave lower values (Fig. 3). The α value has been widely measured by direct or indirect methods in previous studies. For instance, based on a destructive sampling method in different boreal forest species, Gower et al. (1999) measured α values ranging from 0.05 to 0.35. Deblonde et al. (1994) also reported α values of 0.08-0.12 for stands of *Pinus resinosa* by the direct method. However, this method is destructive and labor intensive, and too difficult to be used in the assessment of α values at a stand level. In contrast, the use of indirect techniques (*e.g.*, DHP or LAI-2000) to estimate WAI in leafless periods and its subtractiion from the optical LAI in leafy periods is more practical. For example, Bréda (2003) investigated 70 oak stands during the leafless and leafy periods within a year, finding that α ranged from 0.07 to 0.40. However, this method is only effective in deciduous forest stands since evergreen or mixed deciduous-evergreen forests have no leafless periods. Additionally, previous results are larger than ours (α in the scope of 0.03-0.08), probably because the seasonal variation of the contribution of woody materials to the LAI was not considered in most previous studies. Nevertheless, this contribution varies with the season as the expanded leaves mask some woody materials (*e.g.*, branches), especially in peak LAI period. Similar viewpoints have been reported. For instance, Dufrêne & Bréda (1995) reported that during the full-leaf period (as in this study), only stems accounted for the WAI. Kucharik et al. (1998) also reported that branches generally do not significantly bias indirect LAI measurements, but the stems may not be preferentially shaded by leaves. These results provide theoretical support for the usage of the PS software for an effective quantification of the visible stem area. In addition, if the WAI was directly subtracted from the optical LAI in leafy periods in DL forest stands (deciduous forest), the error caused by woody materials was overestimated by 32% and 21% for DHP and LAI-2000, respectively. Therefore, it is very necessary to consider the seasonal changes of the contribution of woody materials in correcting the optically estimated LAI in further research.

As for a needleleaf forest stands, the clumping effects within canopies can be grouped into two levels, the clumping effects beyond (corrected by Ω_E) and within shoots (corrected by γ_E). The determination of Ω_E by DHP-TRAC has been previously recommended (Leblanc et al. 2005, Chen et al. 2006, Macfarlane et al. 2007). In this study, Ω_E ranged from 0.89 to 0.92 in different forest stands. Similar results have been reported in the majority of published studies in different forest stands. Chen et al. (2006) reported that the Ω_E values ranged from 0.88 to 0.96 by DHP-TRAC in different forest types. To date, measurement of the γ_E values often relies heavily on the destructive sampling method in the field. In the present study, γ_E ranged from 1.08 to 1.46, primarily depending on the relative abundance of broadleaf and needleleaf species in the stand. Similar values were reported by Chen (1996) for six black spruce (*Picea mariana*) and jack pine (*Pinus banksiana*) stands (γ_E = 1.48) and by Kucharik et al. (1998) for coniferous species (γ_E ranging from 1.2 to 2.0). Although the accuracy of the DHP LAI after correction for woody materials, clumping effects within canopies and automatic exposure was improved greatly, the corrected LAI from DHP underestimated the LAI_{lit} by 21% in KP. In our opinion, such discrepancy is mainly due to the automatic exposure adopted, since the light level in KP is generally lower than in other forest stands because of the high proportion of evergreen needleleaf species. Indeed, such conditions may cause a LAI underestimation due to the automatic exposure larger than the exposure correction for the average light condition. In contrast, the difference between LAI_{lit} and LAI-2000 L_e was less than 7% in different forest stands after considering the woody materials and clumping effects within canopies. This result indirectly supports the viewpoint reported by Chen et al. (1997), that optical measurements combined with shoot sample analysis can produce LAI values for conifer stands that are more accurate than destructive sampling results.

By contrast, the contribution of α and Ω_E to optical LAI differed only slightly among forest stands, while a clear difference among different forest stands was detected for the contribution of γ_E to optical LAI (Fig. 3), probably because γ_E varies with species significantly. In addition, the contribution of α, Ω_E and γ_E to optical LAI differed significantly in most forest stands, except for SB, where needleleaf species are largely less abundant than broadleaf species, the latter accounting for 92% of the total basal area. Therefore, species composition of a forest stand should be given more attention when improving the accuracy of LAI estimated by optical methods in future studies.

A significant correlation between the LAI estimates by DHP and by LAI-2000 is shown in Fig. 4. Similar relationships have been reported in other studies, *e.g.*, Martens et al. (1993) in a mixed conifer forest, Chen et al. (1997) in boreal forests and Thimonier et al. (2010) in 15 plots of the Swiss Long-Term Forest Ecosystem Research Programme. However, DHP L_e underestimated LAI-2000 L_e by an average of 37-56% (Tab. 3), probably because of the automatic exposure setting for DHP. Additionally, Fig. 3 showed that the largest uncertainty of DHP L_e was the automatic exposure setting. Automatic exposure is used to create a certain brightness of the image; under low light conditions the exposure increases, causing overexposure of leaves that receive skylight at the top, and determining the underestimation of LAI using DHP. Zhang et al. (2005) reported that automatic exposure can cause L_e underestimations by 16-71% for medium- and high-density canopies. Therefore, not only the woody materials and clumping effects but also the correct exposure setting should be carefully considered estimating LAI using the DHP method in further research.

Conclusions

Based on litter collection, we directly estimated the LAI in four mixed deciduous-evergreen forests and one deciduous needleleaf forest. The results were used to evaluate two conventional indirect optical methods (DHP and LAI-2000). Optical LAI was significantly correlated with litter collection LAI (P < 0.01). However, DHP L_e underestimated LAI_{lit} by an average of 44-70% depending on forest stand. These underestimations range for LAI-2000 were 13-40%. Nevertheless, the difference between LAI_{lit} and DHP L_e after correction for the effect of automatic exposure, woody materials and clumping effects was less than 21%. In contrast, the accuracy of the best estimates of LAI using LAI-2000 was over 93% after considering woody materials and foliage clumping within shoots and the canopy in different forest stands, suggesting that this technique allows to estimate LAI accurately after careful correction. Additionally, the relative contribution of automatic exposure setting to the underestimation of LAI by the DHP technique is larger than other factors (α, Ω_E, and γ_E) in all forest stands, and γ_E has the biggest relative contribution to underestimation of LAI using the LAI-2000 instrument in most forest stands. Such results suggest that species composition of forest stand should also be considered in estimating LAI by optical methods in future studies.

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