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ORIGINAL PAPER

Estimating leaf inclination and G-function from leveled digital camera photography in broadleaf canopies

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Abstract The effectiveness of using leveled digital camera for measuring leaf inclination angles was investigated in this study as an inexpensive and convenient alternative to existing approaches. The new method is validated with manual leaf angle measurements for various broadleaf tree species common to hemi-boreal region of Estonia and the tropical forests of Hawai'i Islands. The acquired leaf angle distributions suggest that planophile case might be more appropriate than the commonly assumed spherical as the general approximation of leaf orientation while modeling the radiation transmission through the canopies of (hemi)-boreal broadleaf stands. However, direct leaf inclination measurements should be obtained whenever possible, as there will always exist a large variety of leaf orientation, both among different species and in the space–time domain within a single species. The camera method tested in this study provides a new robust and affordable tool to obtain this information.

Keywords Leaf inclination angle · G-function · Gap fraction · Digital photography

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Introduction

Directional distribution of leaves is one primary parameter to simulate radiation transmission through the canopy (Warren Wilson 1959; Lemeur and Blad 1974; Myneni et al. 1989). The probability of the transmission of a beam of light through the canopy (P) with a completely random dispersion of the infinitesimal size of the leaves has been commonly described by a 'Beer-Lambert law' function (Monsi and Saeki 1953, 2005):

$$P(\theta) = \exp^{(-G(\theta)L/\cos(\theta))} \quad (1)$$

where L denotes the downward cumulative leaf area index, θ is the view zenith angle, and G is the 'G-function' which quantifies the projection coefficient of unit foliage area on a plane perpendicular to the view direction (Ross 1981). The quantification of G-function requires knowledge of the leaf inclination angle distribution function with leaf inclination angle defined as the angle between the leaf surface normal and the zenith.

A spherical leaf inclination angle distribution (Nichiporovich 1961) is commonly assumed for a vegetative canopy because of the difficulty in estimating real leaf inclination angles. Various methods and instruments for the in situ measurements of leaf inclination angles have been proposed over the years (e.g., Lang 1973; Smith and Berry 1979; Kucharik et al. 1998; Falster and Westoby 2003; Hosoi and Omasa 2007), but their wide-spread use has been generally hampered due to difficulties in applying them to tall canopies, their unsatisfactory ability to reproduce measurements, or high economic costs. Recently, Ryu et al. (2010) introduced a robust and affordable method that allows reproducible measurements of leaf inclination angles based on a digital photography. Unfortunately, Ryu et al. (2010) had no direct measurements available to verify the performance of their method at that time; the targeted canopy was also limited to Blue Oak trees (*Quercus douglasii*) only. This calls for a comprehensive validation of the method using direct measurements of leaf angle inclinations and covering a wider sample of tree species—the common assumption of spherical leaf inclination angle distribution may result in significant underestimation of light transmission through the canopy (Stadt and Lieffers 2000).

In this paper, we report on the validation of the method of estimating leaf inclination angles and *G*-function from the leveled digital photography for various tree species common to hemi-boreal region of Estonia and the tropical forests of Hawai'i. We conclude with discussing the implications of our findings for the modeling of light transmission through the canopy.

Material and method

The approach by Ryu et al. (2010) consists of using a leveled digital camera at several height levels of the canopy. Series of photographs of the surrounding canopy are taken at each level. The photographs are subsequently inspected for the presence of leaves oriented approximately perpendicular to the viewing direction of the camera (i.e., the leaves shown as a line in the image—Fig. 1). The leaf angles of the selected leaves are then estimated using the angle measurement tool of a public domain image processing software (ImageJ; http://rsbweb.nih.gov/ij/). A uniform distribution of leaf azimuth orientation is assumed here. Generally, species indeed do not tend to exhibit any

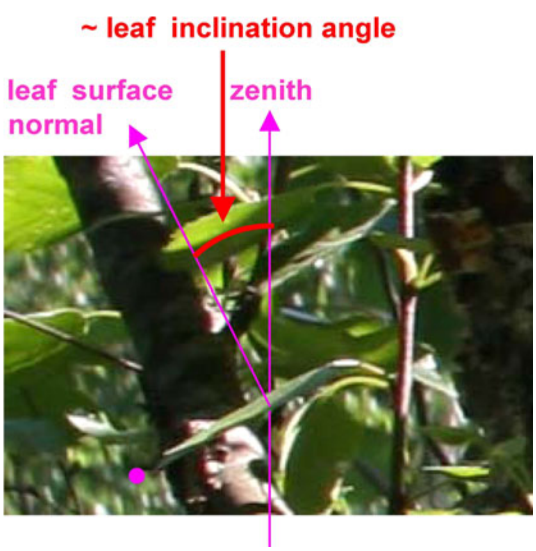

Fig. 1 A schematic diagram of the protocol used to measure leaf inclination angle from leveled digital camera photographs (illustrated on a birch leaf)

characteristic leaf azimuth orientation (Falster and Westoby 2003; but see also e.g. Kimes 1984).

Several special distributions have been developed to describe leaf inclination angle distribution function $f(\theta_L)$ (for their overview see Weiss et al. 2004); Wang et al. (2007) evaluated the two-parameter Beta-distribution (Goel and Strebel 1984) as the most appropriate for describing the probability density of θ_L:

$$f(t) = \frac{1}{B(\mu, v)}(1-t)^{\mu-1}t^{v-1} \quad (2)$$

where t is $2\theta_L/\pi$. The Beta function $B(\mu,v)$ is defined as:

$$B(\mu, v) = \int_0^1 (1-x)^{\mu-1}x^{v-1}\mathrm{d}x = \frac{\Gamma(\mu)\Gamma(v)}{\Gamma(\mu+v)} \quad (3)$$

The leaf inclination distribution can be described by the gamma function Γ and two parameters, μ and v:

$$\mu = (1-\bar{t})\left(\frac{\sigma_0^2}{\sigma_t^2} - 1\right) \quad (4)$$

$$v = \bar{t}\left(\frac{\sigma_0^2}{\sigma_t^2} - 1\right) \quad (5)$$

where σ_0^2 is the maximum standard deviation with expected mean t and $\sigma_t^2$is variance of t (Wang et al. 2007).

While still assuming a uniform distribution of leaf azimuth orientation, G may be finally expressed as (Warren Wilson 1960, 1967):

$$G(\theta) = \int_0^{\pi/2} A(\theta, \theta_L)f(\theta, \theta_L)\mathrm{d}\theta_L \quad (6)$$

$$A(\theta, \theta_L) = \begin{cases} \cos\theta\cos\theta_L, & |\cot\theta\cot\,\theta_L| > 1 \\ \cos\theta\cos\theta_L[1 + (2/\pi)(\tan\psi - \psi)], & \text{otherwise} \end{cases} \quad (7)$$

where θ is view zenith angle, θ_L is leaf inclination angle, and $\psi = \cos^{-1}(\cot\theta\cot\theta_L)$. The values of $G(\theta)$ were calculated with a step of one degree. A trapezoid function was used in the approach of Ryu et al. (2010). Wang et al. (2007) provide further details on the *G*-function calculations.

Results

Two datasets used to validate the approach included the measurements on eight broadleaf tree species from around Tartu Observatory, Tõravere, Estonia, and the Lyon Arboretum and Botanical Garden, University of Hawai'i, Honolulu, USA.

The leaf inclination angle data from the hemi-boreal region of Estonia were obtained in May/June 2010. The sampled tree species included three young Pedunculate Oaks (*Quercus Robur* L.), four Silver birches (*Betula*

Pendula), one Chestnut (*Castanea*), and one Yellow plum (*Ximenia Americana*). First, leaf inclination angles of randomly selected leaves from both inner and outer crowns were measured directly with a clinometer. The birch tree crowns were accessed at several levels from a tower (height 16 m); crowns of oaks, chestnut, and yellow plum were reached using a ladder (height 5 m). Next, we used two leveled digital cameras with a fixed zoom lens (4×) to measure the leaf angles of the same crowns using the approach described above (Fig. 1). The series of images stored in JPEG format were taken up to 10 meters away from the tree crowns. Canon EOS 5D camera was used for the birch trees; Canon PowerShot A610 was used for the other three species.

The second dataset from the Lyon Arboretum and Botanical Garden in Honolulu included the common species of the tropical rainforests of Hawai'i: 'Ōhi'a lehua (*Metrosideros Polymorpha*), 'Ilima (*Sida Fallax*), Māmaki, māmake (*Pipturus Albidus*), and 'Ohe (*Schizostachyum Glaucifolium*). All four Hawaiian species were measured with a clinometer and photographed on August 5, 2010. Canon PowerShot A610 camera was used. The camera settings were the same as in Estonia. Photographs from both datasets were taken during unwind conditions to prevent wind effects on leaves (Kimes 1984). The statistical characteristics of field data are presented in Table 1.

There was a wide range of individual leaf angles in all trees (Fig. 2). In Estonia, leaves with low inclination angles prevailed. The Hawaiian data set showed greater interspecies variation of the leaf inclination angle distribution patterns. The range of mean leaf angles was also close to twice as large for the Hawaiian dataset as of the Estonian dataset (Table 1). Overall, the mean, standard deviation, and the beta distribution of leaf angles obtained from manual and camera measurements agreed quite well for all species. The largest difference in mean leaf angles did not exceed 4° (Table 1).

A two-sample Kolmogorov–Smirnov (K–S) homogeneity test (Sokal and Rohlf 1981) was applied to assess whether the manually measured and digitized leaf angle data were part, as desirable, of the same population. The homogeneity was accepted for all species (Table 2). The highest agreement was observed for *Pipturus Albidus* ($P > 0.628$), while the lowest agreement was for *Castanea* ($P > 0.102$).

Since the difference between the manually measured and digitized leaf angle data was shown to be negligible by the K–S test, Beta-distribution function was fitted to the digitized leaf angle data and $f(\theta_L)$ was developed (Fig. 2). Finally, we characterized $G(\theta)$ using $f(\theta_L)$ (Eq. 6). The $G(\theta)$ was close to that of the planophile orientation (de Wit 1965) for all species except 'Ōhi'a (∼uniform orientation) and 'Ohe (spherical case) (Fig. 3).

Discussion

The results indicate that using digital photography for measuring leaf angles can indeed deliver equivalent results to manual sampling for various ecosystems. The new tested camera approach offers several practical advantages over the other existing methods. First, the method is simple and much more affordable compared to the costs of 3-dimensional digitizers or ground based LiDAR systems. Furthermore, comparable performance was achieved using 12.8 megapixel digital single-lens reflex camera (Canon EOS 5D) and 5.0 megapixel digital budget camera (Canon PowerShot A610). Second, manual sampling with clinometer requires direct access to the canopy; the camera method is thus less restrictive as the leaves can be photographed even from a relatively large distance, this

Table 1 The statistical characteristics (i.e., count, mean, standard deviation) of field manual, leveled digital photography measurements, and mean and standard deviation of fitted Beta functions

Species name	Count	Clinometer		Digital photography (DP)			beta distribution from DP	
		Mean	SD	Count	Mean	SD	Mean	SD
Estonia								
Silver birch (*Betula pendula*)	90	31.62	16.1	317	33.5	17.3	33.53	17.3
Oak (*Quercus robur L.*)	540	24.96	16.5	825	25.22	17.7	25.40	17.6
Chestnut (*Castanea*)	300	27.52	16.2	328	30.22	19.2	30.91	19.1
Yellow plum (*Ximenia Americana*)	120	19.02	13.0	101	18.1	14.3	18.41	14.2
Hawai'i								
'Ōhi'a lehua (*Metrosideros polymorpha*)	93	52.19	26.4	125	49.07	23.6	48.98	23.5
Ilima (*Sida fallax*)	90	25.02	15.8	98	27.58	20.2	27.96	20.1
'Ohe (*Schizostachyum glaucifolium*)	93	54.66	14.1	104	57.11	13.5	57.11	13.5
Māmaki, māmake (*Pipturus albidus*)	93	30.3	12.5	90	32.16	13.8	32.16	13.8

The statistical characteristics for field manual and leveled digital photography methods are calculated based on actual measurements

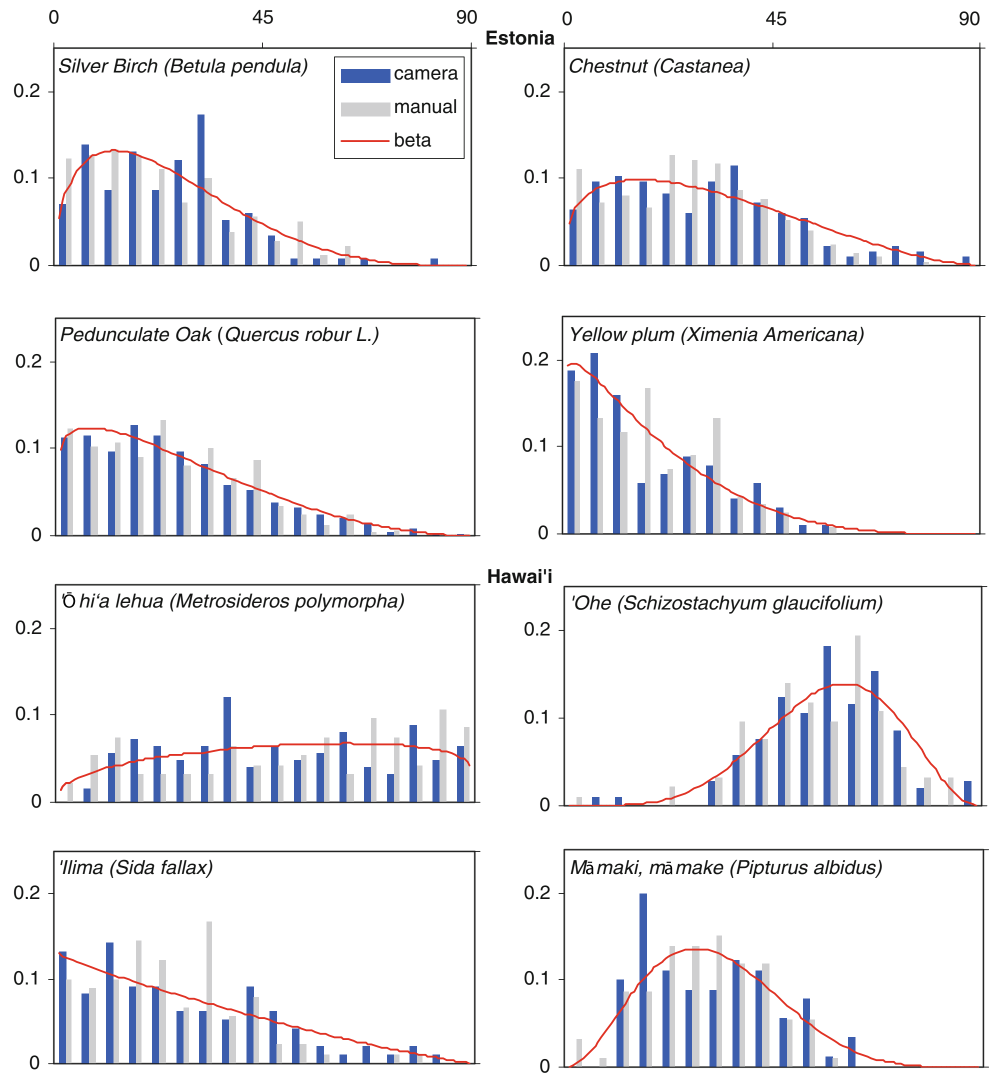

Fig. 2 Frequency distributions of leaf angle of the studied species. Frequency distributions based on the manual method, leveled digital photography, and fitted beta distributions are plotted for each species

Table 2 The results of Kolmogorov–Smirnov test comparing the manual and digital photography-based measurements of leaf inclination angles θ_L from Table 1

Species name	*D*	*P*
Silver birch (*Betula pendula*)	0.087	0.619
Oak (*Quercus robur L.*)	0.055	0.275
Chestnut (*Castanea*)	0.097	0.102
Yellow plum (*Ximenia Americana*)	0.139	0.219
‘Ōhi’a lehua (*Metrosideros polymorpha*)	0.137	0.253
Ilima (*Sida fallax*)	0.145	0.257
‘Ohe (*Schizostachyum glaucifolium*)	0.113	0.535
Māmaki, māmake (*Pipturus albidus*)	0.109	0.628

The maximum difference between the cumulative distributions, *D*, and corresponding level of probability, *P*, are provided

depending on the camera lens. Ryu et al. (2010) were able to detect and measure the leaf angles on the images of tree crowns being 10–15 m away; similar performance was observed in this study as well. Third, the recorded images can be stored on a computer for later review.

The camera method has its limitations as well. The method is applicable to canopies with rather flat leaves. For non-flat leaves, the leaf area of each section would have to be known as well in order to calculate the *G*-function (e.g., following the method described by Ross and Nilson (1965)). Since the measured leaves by the camera method need to be oriented approximately perpendicular to the viewing direction of the camera, the leaf area of sections with different angles cannot be determined this way. It is also practically impossible to measure azimuth angle with this camera method. Similar to

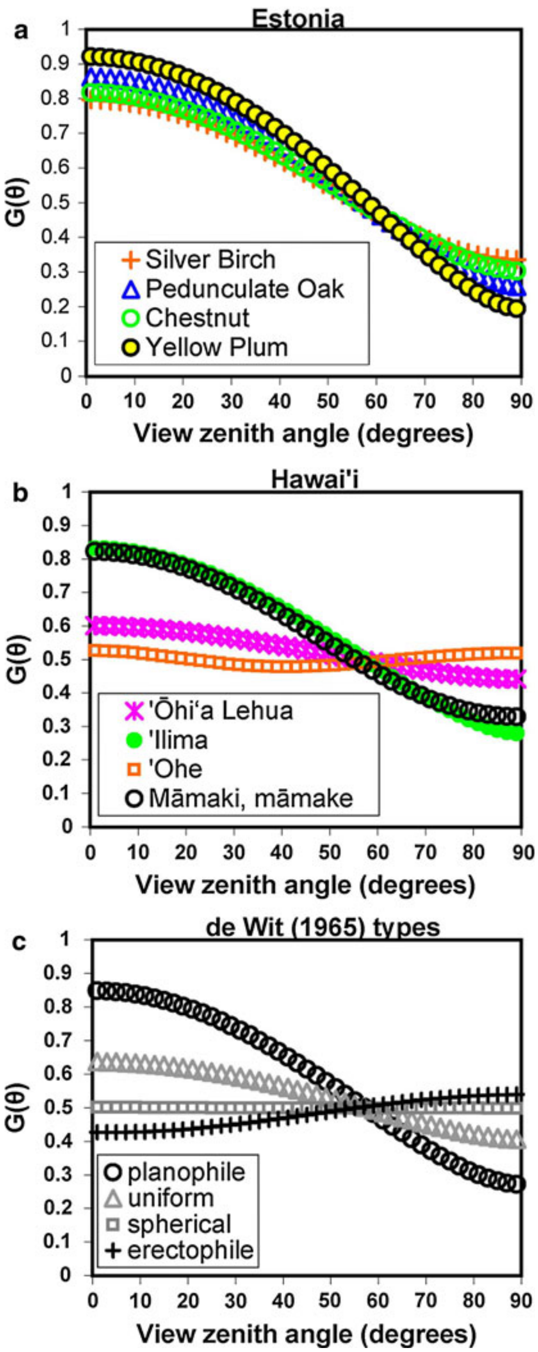

Fig. 3 Leaf projection function (*G*) for the examined broadleaf species in (**a**) Estonia and (**b**) Hawai'i against view zenith angle (θ). **c** Planophile, uniform, spherical, and erectophile cases were drawn for comparison based on de Wit (1965)

other indirect methods, the digital camera method might not be relevant to needleleaf trees (Stenberg 2006) because it is unlikely to capture individual needles from some distance. The most important caveat in the camera method is to randomly sample the leaves to avoid any subjectivity.

As to the observed leaf inclination angles in this study, the distributions were coincident to the planophile with an exception of 'Ōhi'a and 'Ohe species from the Hawaiian dataset. The planophile case has been also previously found e.g., in hazel trees (Chen et al. 1997), oak-hickory forest (Baldocchi et al. 1985), willow coppice plantation (Mõttus 2004), alder (Mõttus unpub. data), orange (Stamper and Allen 1979) and olive trees (Mariscal et al. 2000), birch (Pisek et al. 2011) and many late-succession forests (McMillen and McClendon 1979; Fleck et al. 2003; Pearcy et al. 2004). These results question the common practice of assuming the spherical leaf angle distribution, especially for the hemi-boreal region (Fig. 3). Indeed, planophile was previously identified as the more preferable case for the plant canopies in northern latitudes by theoretical computations of Oker-Blom and Kellomaki (1982), who found photosynthesis in horizontal leaves to be greater than that in the vertical ones for leaf area index values up to 6. The implications are not limited to photosynthesis only—Baldocchi et al. (2002) found large differences in CO_2 exchange (NEE), latent and sensible heat exchange fluxes while considering planophile and spherical/erectophile cases as well. Hikosaka and Hirose (1997) also noted the greater capacity of species with planophile foliage orientation to shade out the species with vertical foliage orientation while simultaneously having a higher foliage shade tolerance as well. Based on our results and the above presented findings, we would consider planophile leaf angle distribution as possibly more appropriate while modeling the radiation transmission through the canopies of (hemi)-boreal broadleaf stands and when no real leaf inclination measurements are available. However, direct leaf inclination measurements should be obtained whenever possible, as there will always exist a large variety of leaf orientation, both among different species and in the space–time domain within a single species (Ross 1981; Niinemets 1998; Kull et al. 1999; Utsugi 1999; Niinemets 2010). The camera method tested in this study provides a new robust and affordable tool to obtain this information.

Conclusion

The effectiveness of using leveled digital camera for measuring leaf inclination angles was investigated in this study as an inexpensive and convenient alternative to existing approaches for several broadleaf tree species from two contrasting environments. The method was shown to be capable of delivering equivalent results to manual measurements, while simultaneously providing advantages of simplicity, affordability, not requiring direct access to the canopy, and storing the information for later review as well.

Our limited samples showed planophile case for tree species in the hemi-boreal region. As planophile leaves show very different canopy fluxes compared to spherical, we recommend research community collecting more leaf angle samples in this region to better quantify regional CO_2 and H_2O fluxes.

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