Short Paper

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Estimating leaf inclination angle distribution of broad-leaved trees in each part of the canopies by a high-resolution portable scanning lidar

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Abstract

We estimated the distribution of leaf inclination angle (LIA) throughout the canopy of three broad-leaved trees by a portable high-resolution scanning lidar. Each canopy was scanned from three positions surrounding it and the data were co-registered. The 3-D images were divided into five horizontal layers, and the LIA distribution of each layer was estimated by a fitted plane to each leaf and taking the zenith angle of the plane. The LIA decreased significantly with increasing canopy height. The degree of the LIA decrease was different in each specimen. The mean LIA values of each layer were 36.7° to 43.8° in *Camellia sasanqua*, 34.6° to 45.9° in *Osmanthus fragrans*, and 48.9° to 65.4° in *Camellia japonica*. The differences in LIA distribution were explained mainly by the light conditions around the trees.

Key words: 3-D, Broad-leaved tree, Canopy, Leaf inclination angle, Portable scanning lidar.

1. Introduction

Leaf inclination angle (LIA) distribution is one of 3-D structural properties of a plant canopy. LIA distribution has been often related to light environment within the canopy and photosynthetic productivity (Muraoka *et al.,* 1998; Valladares *et al.,* 2000; Niinemets and Fleck, 2002; Niinemets, 2010; Utsugi *et al.,* 2006). It has been also reported that plants decrease the leaf temperature by adjusting the LIA more vertically (Medina *et al.,* 1978; Muraoka *et al.,* 1998). It has been suggested that leaf inclination angle may affect the way in which water droplets are channeled off leaf surfaces (Wu, *et al*., 2014) and more vertical leaf inclination increase through-fall to the soil (Holder, 2012). Thus, it is important to take account of LIA distribution within the canopy for understanding the mechanism of plant adaptation to various environmental factors. LIA distribution has been measured by clinometer (Gratani and Ghia, 2002), protractor and compass (Norman and Campbell, 1989), and 3-D digitizer (Sinoquet *et al.,* 1998). These methods, however, are labor-intensive, and thus it is hard to measure many leaves. LIA can be also measured by the indirect gap-fraction method with commercially available tools such as cameras with fisheye lenses and optical sensors (Welles and Norman, 1991). Although this method allows quick data collection, it provides mean LIA rather than a detailed spatial distribution. In addition, its accuracy is affected by the leaf spatial distribution and light conditions. Recently, portable scanning lidar (light detection and ranging) instruments have been used to measure 3-D structural properties of plants (Hosoi and Omasa, 2006, 2007; Omasa *et al.,* 2007; Côté *et al.,* 2009; Hosoi *et al.,* 2011; Dassot *et al.,* 2011). A portable scanning lidar measures the distance to the target from the elapsed time between the emission and return of laser pulses (the time-of-flight method) or by trigonometry (the optical-probe or light-section methods). It can record many 3-D point cloud data of a target quickly and automatically with a ranging accuracy of milimeter to centimeter, overcoming the shortcomings of conventional LIA measurements in both accuracy and data collection efficiency. In particular, a high-resolution portable scanning lidar with a range accuracy and resolution of about 1 mm and a beam divergence of a few mrad can clearly capture the 3-D shape of each leaf, and thus is suitable for LIA measurements. Through the use of such an instrument, the LIA distributions of some tree species have been extracted (Hosoi and Omasa, 2007; Hosoi *et al.,* 2014). Its data collection efficiency allows repeated measurements, and so it has been also used to measure seasonal changes in LIA distribution in broad-leaved trees (Hosoi and Omasa, 2009) and the LIA distribution of crops at each growth stage (Hosoi and Omasa, 2012; Hosoi *et al.,* 2009). These studies have shown the usefulness of high-resolution portable scanning lidar for LIA measurements in specific parts of the canopy. However, the LIA distribution changes depending on the position in the canopy. For instance, it has been often observed that LIA changes gradually from more vertical in the upper canopy to more horizontal in the lower canopy (Niinemets, 2010; Utsugi *et al.,* 2006). Such variation improves light interception in the lower canopy and enables the upper canopy to intercept less potentially damage from midday solar radiation and to allow more light to reach the lower canopy (Niinemets, 2010). Thus, it is important to consider differences in LIA in each part of the canopy for a clear understanding of canopy function. The difference in LIA can be examined by measuring the LIA distribution of each positon in the canopy and comparing them. Since a large number of leaves must be measured for obtaining the distribution of each part, the traditional methods like use of a clinometer or protractor are not suitable for the purpose. In terms of accuracy and data collection efficiency, portable scanning lidar might be able to be used for capturing difference of the LIA distribution in each part of the canopy. However, the ability of the lidar for the purpose has not yet been fully demonstrated. In the present study, we demonstrate the capability of the portable scanning lidar to offer accurately and efficiently difference of the LIA distribution in each part of the canopy, where whole canopies of broad-leaved

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trees are scanned by a high-resolution portable scanning lidar and our developed method to retrieve LIA from lidar image is applied. Then, through analysis of resultant LIA distributions, it is shown the usefulness of the lidar-derived LIA distributions of each part of the canopy in understanding of canopy function.

2. Material and Methods

The experiment was conducted at a mixed plantation in Ibaraki Prefecture, 40 km northeast of central Metropolitan Tokyo, Japan (35°59′N, 140°02′E), that belongs to a temperate region with the average temperature of 14.1℃ and the annual precipitation of about 1373 mm (in 2008). We chose three broad-leaved trees as specimens: *Camellia sasanqua* Thunb. (2.05 m tall), *Camellia japonica* L. (2.53 m), and *Osmanthus fragrans* Lour. var. *aurantiacus* Makino (2.56 m). Since these specimens were different species with different structure, they seemed to be suitable for evaluating the applicability of the proposed method. The heights of the specimens were favorable to the measurable range of the present lidar instrument (3.5 to 10.0 m, described later). Each tree was surrounded by open space with good light and thus positions to set up a portable scanning lidar could be easily found.

A portable high-resolution scanning lidar (a modified TDS-130L 3-D laser scanner; Pulstec Industrial Co., Ltd., Japan) was used to scan the specimens. The lidar calculates distances by trigonometry, and has a range resolution of ~1 mm and a scan resolution of ~2 mm at a measurement range of ~5 m with the measurable range of 3.5 to 10.0 m. The resolution becomes coarse as the distance to a target becomes long. A rotating mount with a stepper motor and a galvano mirror within the lidar head automate the horizontal and vertical scanning. To capture the whole canopy, we set three equidistant measurement positions around each tree at about 4.6 m from each tree. The distance to the targets allowed to obtaining the lidar images with the spatial resolution fine enough to estimate LIA. The central zenith angle of each laser scan was 87° for the *C. sasanqua*, 84° for the *C. japonica*, and 85° for the *O. fragrans*. Those angles near 90° were chosen for more laser beam penetration into the internal canopy based on the finding reported in our previous study (Hosoi and Omasa, 2007). Each position was about 120° apart from each other towards azimuth direction. The measurement dates were 10 October for *C. sasanqua*, 21 October for *C. japonica*, and 26 November for *O. fragrans*, in 2013, with fine weather condition. Since the daytime was windy, the measurements were conducted at night when wind became weak. It took about twenty minutes per one scan. The lidar data acquired from the three positions per tree were co-registered using the iterative closest-point (ICP) algorithm (Besl and McKay, 1992) to generate 3-D point cloud images of the whole canopies.

To capture differences of LIA in each part of the canopy, we divided the canopy within each 3-D image into five horizontal layers with thicknesses of 0.29 m in *C. sasanqua*, 0.39 m in *C. japonica*, and 0.38 m in *O. fragrans*. Since the resolution of the obtained lidar images was fine, each leaf shape was distinguisha-

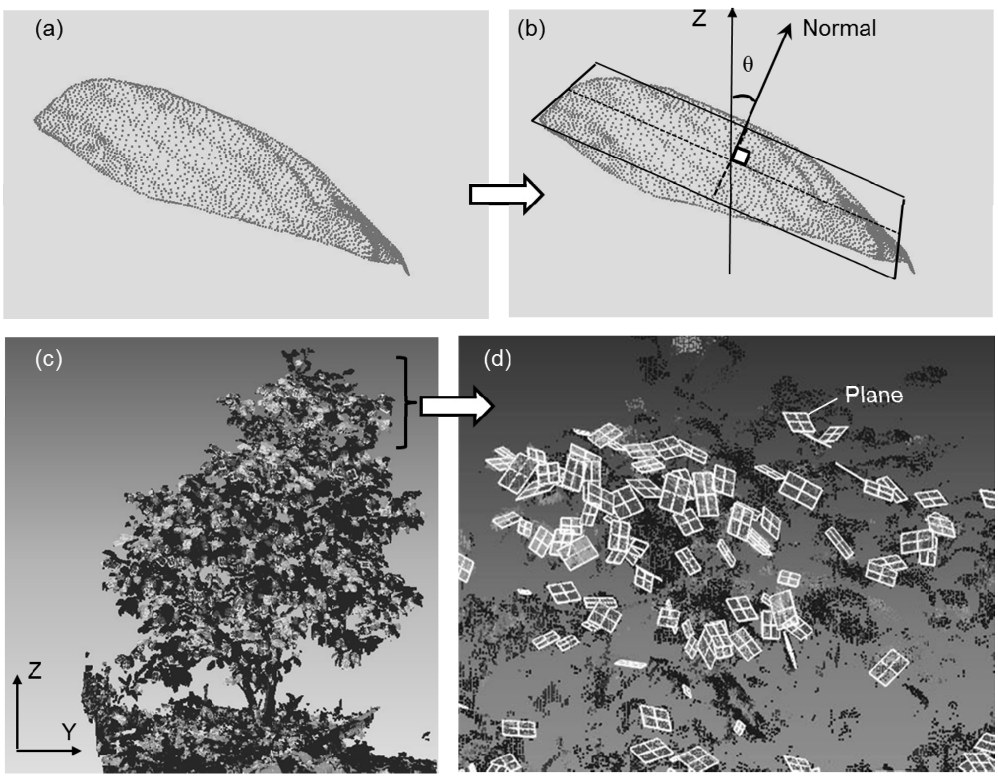

Fig. 1. Estimation of LIA from the high-resolution portable scanning lidar data. (a) An example of a set of points corresponding to a leaf. (b) A plane fitted to a point set of a leaf. θ is the LIA, derived from the angle of the normal with respect to the zenith. (c) An example of planes fitted to each of 500 leaves within a 3-D point-cloud image. Shading effect by top light is added. (d) Close-up view of c, showing many planes fitted to leaves.

ble in the images. Then by eye we interactively picked out 100 leaves per each layer (500 leaves per tree), using a software attached to the present lidar instrument. The points that composed each leaf were fitted to a plane by a least-squares method, and normals to the planes were calculated (Fig. 1). The LIA distribution was derived from the angles of these normals with respect to the zenith (Hosoi and Omasa, 2007). We compared mean LIA values among layers of each tree and among trees. We also combined the upper two layers ("upper region") and the lower three layers ("lower region") to compare LIA between the southern and northern sides of each tree (determined from a vertical central cross-section of a lidar image). For all comparisons we used Welch's *t*-test of all possible combinations at $P < 0.05$ with the Bonferroni method.

To evaluate the accuracy of the lidar-derived LIA distribution, we cut some branches from each tree and took them back to the laboratory. The branches were laid on a stand and scanned. Then the LIA values of 30 leaves of each specimen were estimated as above. To measure the actual LIA values, we measured the inclination of the same leaves by clinometer (A-150; Shinwa Measuring Tools Corp. Japan), and then compared the values to assess the accuracy of the lidar estimates.

3. Results and Discussion

The lidar-derived point cloud images allowed each leaf to be distinguished (Fig. 2). Therefore, LIA could be estimated from the plane of each leaf. Comparison with laboratory measurements gave mean absolute errors of 2.4° for *C. sasanqua*, 2.3° for *C. japonica*, and 2.8° for *O. fragrans*. Thus, LIA could be estimated accurately from the lidar data. In each tree, the mean LIA value decreased gradually with increasing canopy height (Figs. 3, 4). In all trees, the differences between the top and bottom layers, as well as between some other layers, were significant (Fig. 3). The mean LIA of the *C. japonica* was significantly larger than those of the other two trees in all layers (Fig. 3). The mean LIA values of the southern (sunward) side of the *C. japonica* were significantly larger than those of the northern side in both the upper and lower regions, but there were no significant differences in the *C. sasanqua* or *O. fragrans* (Fig. 4). As shown in the results in Fig.3 and 4, difference of LIA in each part of the canopies could be obtained by the present method using a high resolution portable scanning lidar. In traditional methods used to measure LIA (*e.g.*, by protractor), it can be both laborious and difficult to measure LIA in different parts of the canopy, particularly in the higher part. In addition, the measurement is often affected by wind, because it takes long time and windless conditions rarely last long. Thus, the measurement accuracy may not be maintained due to the disturbance by wind. On the other hand, a high-resolution portable scanning lidar can record quickly the whole canopy (about twenty minutes per one scan at the present instrument) including the higher part of the canopy where LIA measurement is difficult by traditional methods and any part of the canopy can be extracted from the point-cloud image. Thus, the LIA distribution of any part of the canopy can be efficiently and quickly obtained without intensive effort. The ranging accuracy of milimeter allows accurate results with the mean absolute errors of less than 3.0°, in the case of the present lidar instruments. Since the measurement time is shorter than the traditional methods, the data can be taken quickly during brief windless condition, resulting in less influence of wind on the LIA estimation. Thus, in terms of the efficiency and accuracy, the proposed method to obtain difference of LIA in each part of the canopy is more advantageous than the traditional methods.

LIA distribution is affected by environmental conditions, in particular light. At our site, there was open space around the trees with good light. In such an open environment, LIA tends to increase (Niinemets and Fleck, 2002; Valladares *et al.,* 2000; Muraoka *et al.,* 1998), because plants decrease light interception by inclining their leaves more vertically, creating a more uniform light distribution within the canopy and avoiding excessive radiation and the consequent water stress and photoinhibition of photosynthesis (Muraoka *et al.,* 1998). However, this does not offer

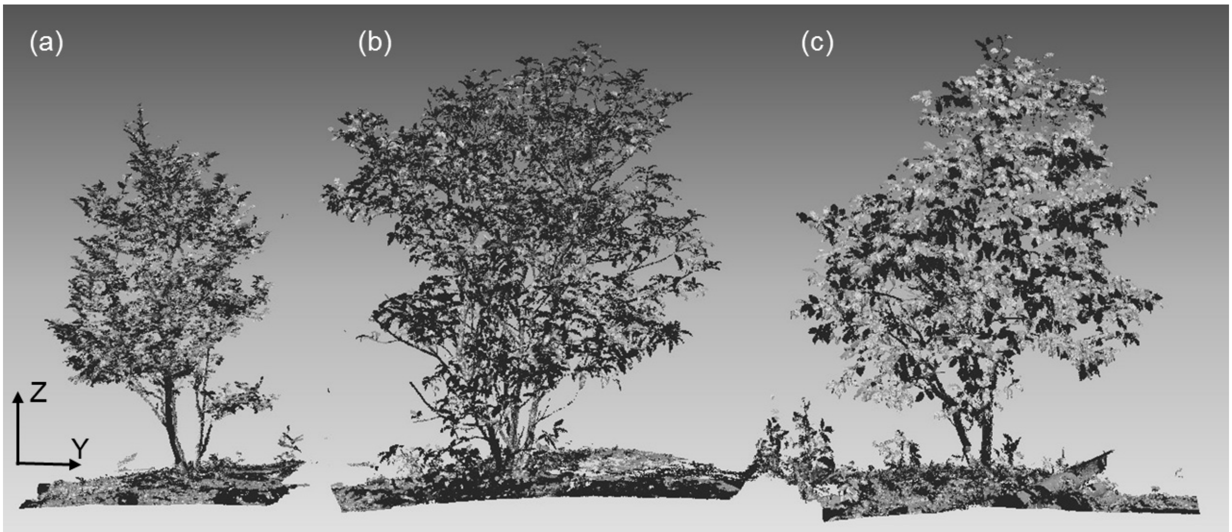

Fig. 2. 3-D point cloud images of (a) *Camellia sasanqua*, (b) *Osmanthus fragrans*, and (c) *Camellia japonica* obtained by high-resolution portable scanning lidar. Shading effect by top light is added.

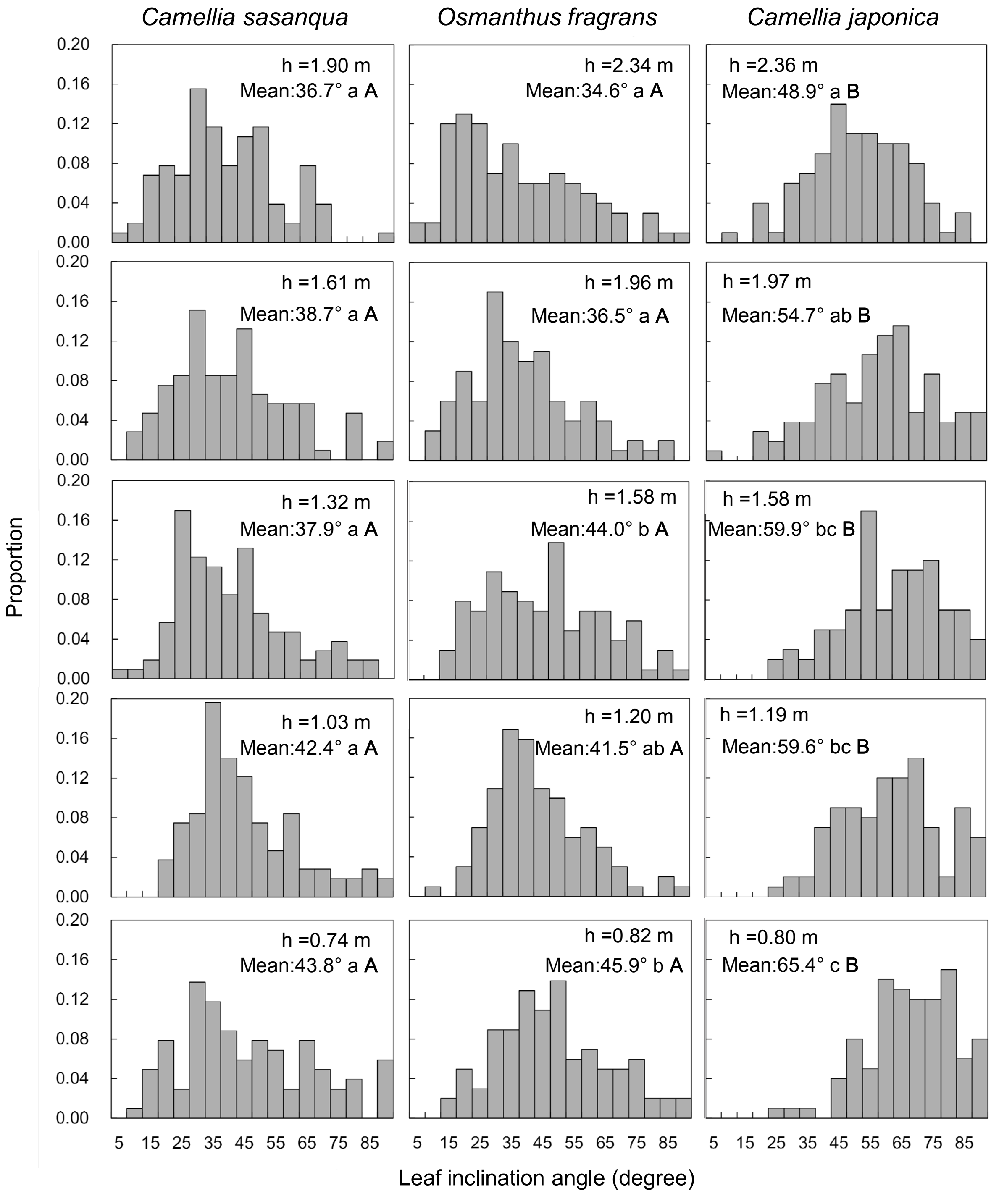

Fig. 3. Lidar-derived LIA distributions at each height in each tree. Small letters mean significant difference of the distribution between layers in the same tree and capital letters mean the significant difference between trees in the same layer. Means followed by the same letters in each layer or each tree are not significantly different at $P < 0.05$ by the Bonferroni method. h is height corresponding to a center of a layer.

well explanation from our results because the mean LIA was smaller in the upper layers than in the lower layers, nevertheless the available light was more in the upper layers than in the lower ones. Our sample trees might not have decreased the light interception but increased it. They may have increased the LIA in the upper layer so as to capture solar radiation from all directions. As the height decreases, leaves become difficult to capture radiation from the upper due to the obstruction by the upper canopy and thus they may have increased the LIA in their lower layers so as to capture more radiation from the sides which is relatively well available in the open space. The differences between layers in the *C. sasanqua* were smaller than those in the *C. japonica*, possibly because the *C. sasanqua* had a lower leaf area density, allowing lower leaves to capture more radiation from above than in the *C. japonica*. These results thus suggest that LIA is well explained in terms of adaptation to the light environment. Besides light adapta-

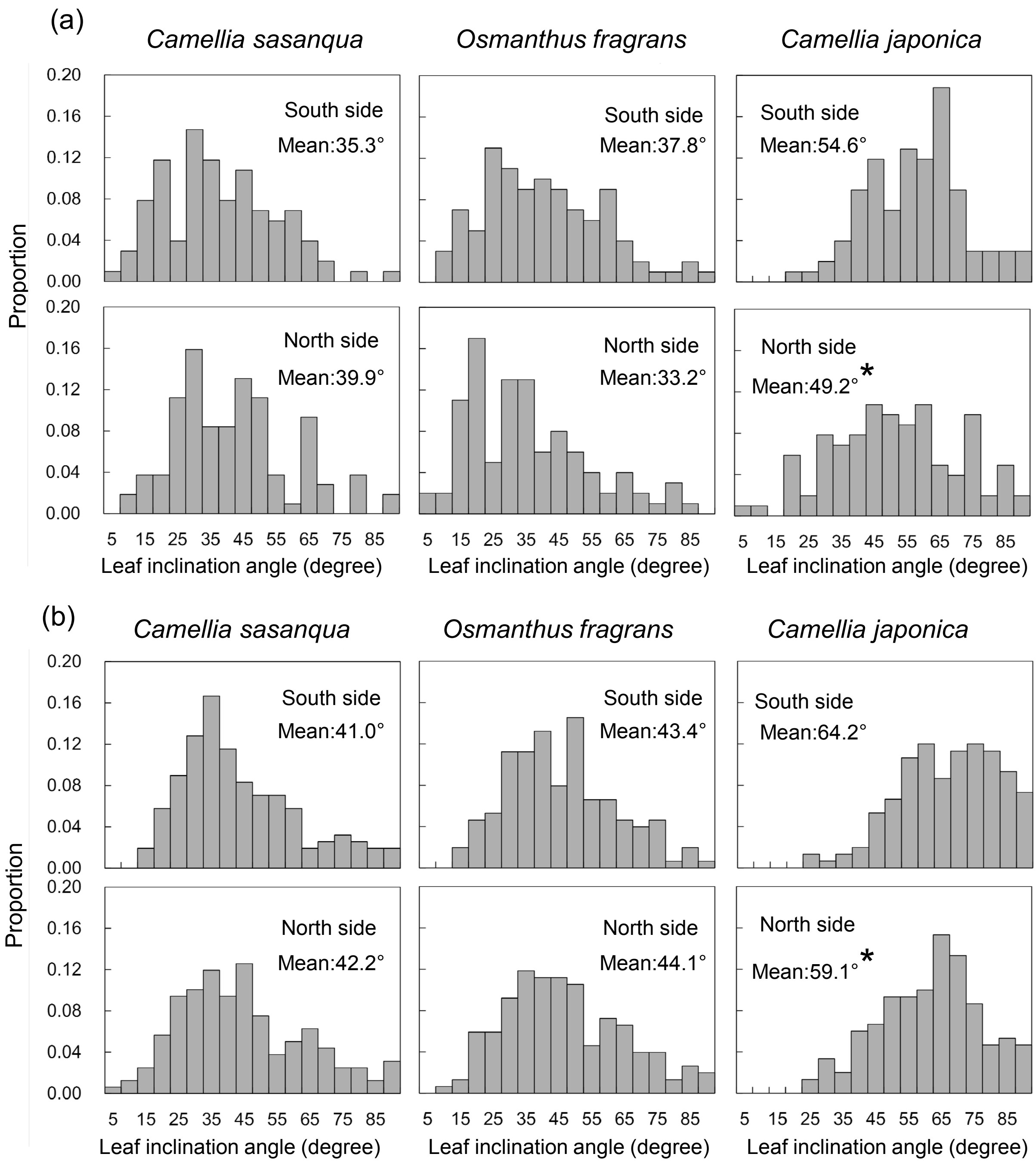

Fig. 4. LIA distributions on the southern and northern sides of each tree in (a) the upper two layers and (b) the lower three layers. An asterisk (*) means significant difference between the southern and northern sides in the same tree at $P < 0.05$.

tion, the tendency may reflect species specific characteristics of LIA. Our study did not allow us to discriminate both contributions. Thus, the results obtained by the proposed method provided detailed information about the LIA distributions of the specimens and allowed to discuss the relationship between the canopy structure and function. This shows the usefulness of the structural information obtained by the proposed method for understanding of canopy function. For obtaining more knowledge about canopy function, it is an useful way to combine the LIA information with other structural information such as leaf area density (Hosoi and Omasa, 2006) or physiological information obtained by thermal or multispectral images (Omasa *et al.,* 2007). In addition, the LIA information would be also able to be used as input data for plant modeling (Valladares and Pearcy, 2000; Kobayashi and Iwabuchi, 2008). Besides LIA measurements, azimuth directions of leaves would be also measurable using this method, offering useful information to study canopy function, such as canopy light interception (Barradas *et al.,* 1999) or seasonal change of canopy structure (Gratani and Ghia, 2002).

4. Conclusions

We obtained accurate LIA distributions of the entire canopy of three broad-leaved trees by portable high-resolution scanning lidar. The LIA of individual leaves was estimated by fitting a plane to each leaf and calculating the zenith angle of each. The LIA decreased significantly with increasing canopy height, depending on the specimen. The LIA distribution differed significantly between the *C. japonica* and the other two trees and between the southern and northern sides of the *C. japonica* tree. The differences in LIA distribution were explained by the light condition around the trees. Our results show that our lidar method can offer effectively and accurately differences of LIA distributions in each part of the canopy and the lidar-derived data are useable for improving researchers' understanding of the relationship between LIA and plant function. Using this method, other species and environmental conditions are desirable to be examined in the additional works.

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