Original Paper

Estimation of Leaf Area Density Profiles of Japanese Maple and Camellia Woody Canopies Using Portable Scanning Lidars

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ABSTRACT

We estimated the vertical profiles of leaf area density (LAD) of Japanese maple and camellia canopies in a woody area by using portable scanning lidar. 3D point cloud data on the canopies were collected by lidar from several points on the ground. Appropriate selection of ground points allowed the targets to be well scanned in spite of the presence of several trees around them. LAD profiles were computed by using the voxel-based canopy profiling method. The maximum and mean LAD values were 1.68 and 0.93 $m^2\ m^{-3}$ for the Japanese maple canopy and 0.94 and 0.41 $m^2\ m^{-3}$ for the camellia canopy. Leaf area index values were 1.61 and 3.35 $m^2\ m^{-2}$, respectively. Comparison of these LAD estimates with actual measurements taken in volumes of 2 m^3 within the canopies gave percentage errors of −14.2% in the Japanese maple canopy and −16.4% in the camellia canopy.

Key words : Leaf area density, Portable scanning lidar, Three-dimensional imaging, Voxel-based canopy profiling

1. Introduction

The plant canopy plays important functional roles in the cycling of materials and energy through photosynthesis and transpiration, maintenance of plant microclimate, and provision of habitats for many species (Monteith, 1973; Jones, 1992; Larcher, 2001). Determining the vertical structure of the canopy is important to understanding how the three-dimensional (3D) composition of the canopy helps to sustain those functional roles (Graetz, 1990; Lefsky et al., 2002). Vertical canopy structure is often represented by the vertical distribution of leaf area density (LAD) in each horizontal layer, defined as the distribution of one-sided leaf area per unit of horizontal layer volume (Weiss et al., 2004). Several methods of deriving LAD profiles have been tried. A straightforward method is to take stratified clippings of biomass samples (Monsi and Saeki, 1953), but it has limited applicability in the field because it is destructive and very laborious. An indirect method, the gap-fraction method, is widely applied in field surveys by using commercially available tools such as cameras with fish-eye lenses and optical sensors. This method, which is based on light transmittance through the canopy, allows automatic, nondestructive estimation of LAD. However, the accuracy of the measurements is affected by the spatial distribution of leaves and by the sunlight conditions (Chason et al., 1991; Jonckheere et al., 2004).

Recently, portable scanning lidar (light detection and ranging) has been used to obtain 3D structural properties of plants (Omasa et al., 2002, 2007, 2008; Lovell et al., 2003; Hosoi et al., 2005, 2010; Hosoi and Omasa, 2006, 2007, 2009; Takeda et al., 2005, 2008). The instrument can record many 3D point cloud data of a target quickly and accurately, regardless of

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sunlight. Thus, it has the potential to overcome the shortcomings of conventional ways of measuring LAD. In fact, it accurately and effectively estimated LAD profiles in a Japanese *Zelkova* woody canopy (Hosoi and Omasa, 2007, 2009; Hosoi et al., 2010). However, the applicability of the method has not been demonstrated in other species. To enhance its applicability, the method should be tested in woody canopies of other tree species that have structures different from that of Japanese *Zelkova*. Therefore, we examined its applicability in two other broadleaved tree species.

2. Materials and Methods

2.1 Study site

The experiment was conducted in a woody area within a botanical garden in Shizuoka Prefecture, Japan. About 110 tree species grew in the area, including Japanese cedar (*Cryptomeria japonica* (L. f.) D. Don), Japanese red pine (*Pinus densiflora* Sieb. & Zucc.), Hinoki cypress (*Chamaecyparis obtusa* Sieb. & Zucc.), camellia (*Camellia japonica* L.), oak (*Quercus serrata* Thunb.), and Japanese maple (*Acer palmatum* Thunb.). We established two plots, measuring 7 m × 13 m (plot A) and 6 m × 8 m (plot B). Each plot included many trees of various species with different sizes and structures. A Japanese maple grew at the center of plot A and a camellia at the center of plot B. We selected these as target trees for LAD estimation by lidar measurements.

2.2 Lidar measurements

A portable scanning lidar (LPM-25HA, Riegl, Austria) was used for the 3D measurement in plot A. This model is able to measure distances of between 2 and 60 m. A rotating mount driven by built-in stepper motors with 0.009° accuracy panned and tilted the lidar head. The lidar has a range accuracy of ±8 mm. In September 2009 (leafy period), trees within plot A were scanned by the lidar from four ground positions chosen carefully to fully illuminate the target Japanese maple tree, which was surrounded by many other trees. The center of the zenith angles of the laser beams was 66°. The plot was measured again from the same positions in February 2010 (leafless period), with the same measurement conditions as before.

Another portable, high-resolution scanning lidar that calculates distances by trigonometry (a modified TDS-130L 3D laser scanner; Pulstec Industrial Co., Ltd., Japan) was used to obtain the leaf inclination distribution of the Japanese maple canopy. This model is able to measure distances of between 3.5 and 10 m. Its range and scan resolutions are about 1 mm and 2 mm, respectively, at 5 m. A rotating mount with a stepper motor and a galvano mirror within the lidar head automated the horizontal and vertical scanning. Part of the canopy was scanned from a ground position in September 2009. Each leaf was distinguishable from the 3D point cloud image because of the fine resolution. After randomly selecting 200 leaves in the image, we fitted points within each of the leaves to a plane by the least squares method and estimated normals to the planes. The leaf inclination angle was defined as the zenith angle of the normal. The leaf inclination distribution was derived from the zenith angles.

The smaller size of plot B meant that we could use the TDS-130L scanner for 3D measurements in February 2010. Three ground measurement positions were carefully chosen to fully illuminate the target camellia. The center of the zenith angles of the laser beams was 59°. We also used the lidar to derive the leaf inclination distribution of the camellia canopy as for the Japanese maple.

2.3 LAD computation

We used the VCP (voxel-based canopy profiling) method (Hosoi and Omasa, 2006) to compute LAD in the Japanese maple canopy. The data obtained from the different ground positions were registered into a single point cloud data set for each season with a common 3D coordinate system. Nonphotosynthetic tissues such as trunks and branches were excluded by subtracting the leafless period data from the leafy period data. A voxel array with a voxel size of 5 mm × 5 mm × 5 mm was prepared on a computer. All points within the lidar data were converted into voxel coordinates. Then, all laser beams emitted from the lidar were traced within the voxel array in accordance with the laser emission angles, and voxels were assigned a value of 1 if at least one laser beam was intercepted by leaves and 2 if voxels that did not have a value of 1 were intersected by at least one laser beam. LAD in each horizontal layer was derived by computing the frequency of laser beam contact with leaves from these voxel attribute values. In the computation, the influence of the leaf inclination angle and laser beam direction was corrected by using the correction factor $\cos(\theta)[G(\theta)]^{-1}$, where θ is the mean zenith angle of all laser beam incidences and $G(\theta)$ is the mean projection of a unit leaf area on a plane perpendicular to the direction of the laser beam at θ (Weiss et al., 2004). The correction factor was determined by the mean zenith angle of laser beams and the distribution of leaf inclination angles acquired by the fine-resolution portable lidar (a modified TDS-130L), as described above. More details of the VCP method are given by Hosoi and Omasa (2006).

LAD in the camellia canopy in plot B was similarly computed, using a voxel size of 2 mm × 2 mm × 2 mm. As *C. japonica* is evergreen, nonphotosynthetic tissues were selected by eye and excluded.

2.4 Actual measurements

To validate the lidar-derived LAD estimation, we physically measured leaf area in the Japanese maple in September 2009 and in the camellia in February 2010. As direct leaf sampling was forbidden, we defined regions of 1 m × 1 m × 2 m within each canopy and took digital photographs of each of 50 leaves within the regions with a scale. From the scale, we determined the relationship between the number of pixels in each photograph and the actual leaf area. Using this relationship, we determined the mean area per leaf. We counted all leaves in the 2 m^3 region, and by multiplying the number of leaves by the mean area of a leaf we derived the total leaf area within the region. Dividing the total leaf area by the volume (2 m^3) gave the actual value of LAD in the region. LAD values corresponding to the same region were computed by using the VCP-method, and the accuracy was estimated by comparison.

3. Results and Discussion

The high spatial resolution of the lidar correctly reproduced the densely distributed leaves in each canopy from the co-registered 3D point cloud data (Figs. 1, 2). Both canopies were fully scanned.

The leaf inclination distribution of the Japanese maple canopy did not favor a particular angle (Fig. 3). In contrast, that of the camellia canopy was biased toward lower angles (i.e., a planophile distribution) (Fig. 4).

We plotted the profiles of Japanese maple and camellia canopies (Fig. 5). The estimated LAD profile of the Japanese maple canopy was monomodal, with a peak of 1.68 $m^2\ m^{-3}$ (and a mean of 0.93 $m^2\ m^{-3}$) at around 3.0 m height. That of the camellia canopy was more rectangular, with a peak of 0.94 $m^2\ m^{-3}$ (and a mean of 0.41 $m^2\ m^{-3}$) concentrated

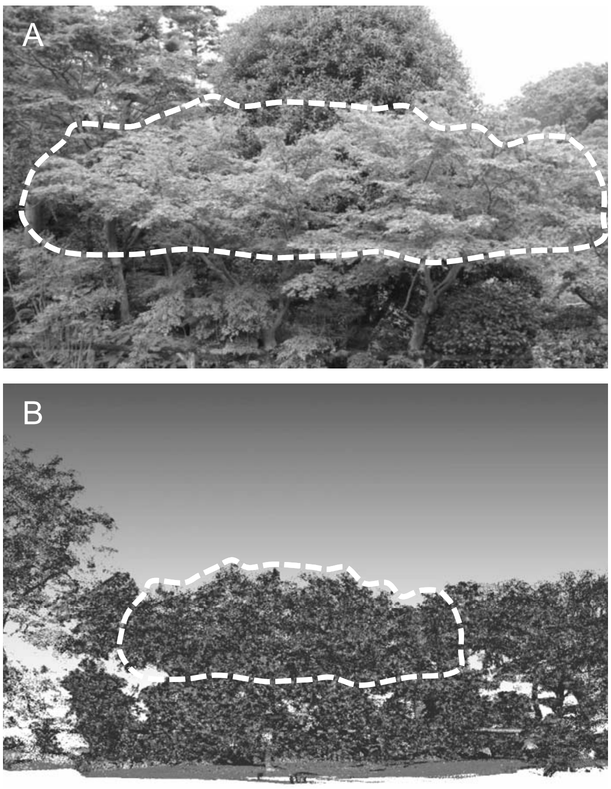

Fig. 1 Plot A (7 m × 13 m). (A) Photograph. (B) 3D point cloud image after co-registration of data measured by using portable scanning lidar. White broken line indicates Japanese maple canopy.

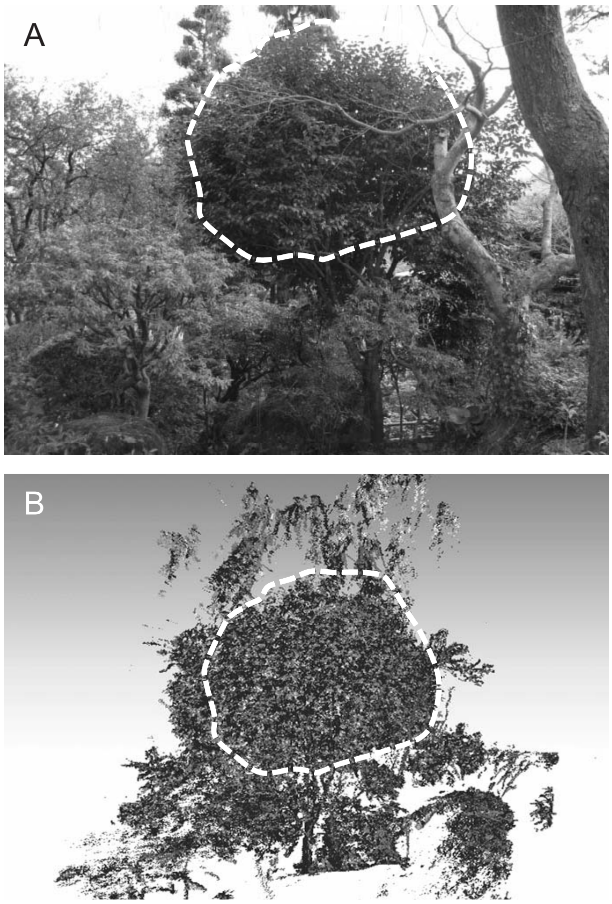

Fig. 2 Plot B (6 m × 8 m). (A) Photograph. (B) 3D point cloud image after co-registration of data measured by using portable scanning lidar. White broken line indicates camellia canopy.

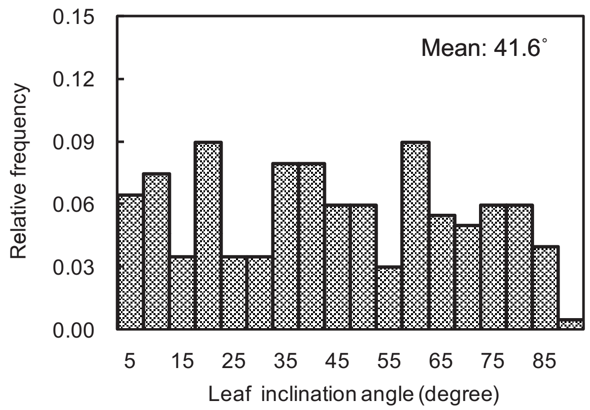

Fig. 3 Leaf inclination angle distribution of Japanese maple canopy.

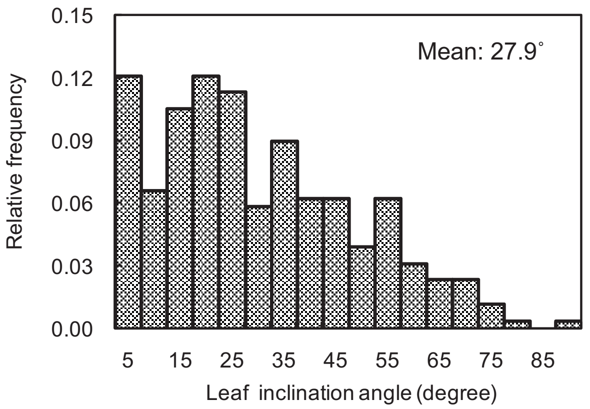

Fig. 4 Leaf inclination angle distribution of camellia canopy.

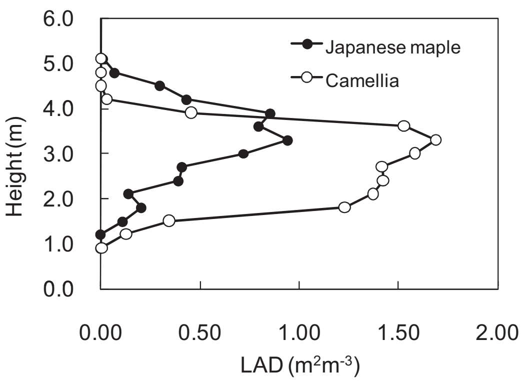

Fig. 5 Lidar-derived vertical LAD profiles of Japanese maple and camellia canopies.

at 2.0 to 4.0 m height. These profiles differed from that of a Japanese *Zelkova* canopy (Hosoi and Omasa 2007), which was monomodal but peaked at 10 m height.

The leaf inclination distributions and LAD profiles showed clear structural differences between the two canopies; these structural differences reflect species differences and might have caused differences in the light environment between the two canopies.

Comparison of measured LAD values within the canopies with the corresponding lidar-derived values gave percentage errors of −14.2% for the Japanese maple canopy and −16.4% for the camellia canopy. Vertical integration of LAD values gave LAI values of 1.61 m^2 m^{-2} for the Japanese maple canopy and 3.35 m^2 m^{-2} for the camellia canopy. The camellia's denser canopy may have reduced the accuracy of estimation by reducing canopy penetration by the laser. Nevertheless, the percentage errors were low. Because leaves grew more densely in the 2-m^3 regions than in other regions of the target canopies, the accuracy of LAD estimation in those regions would have been representative of the accuracy for the whole canopies. This result demonstrated that our method was effective at estimating the LAD of the canopies of tree species that had different structural properties, such as leaf inclination distributions and LAD profiles. The low error would have in part been due to the appropriate selection of ground lidar positions around the targets, ensuring enough penetration into the canopies. This meant that our method could cope with structural differences among even relatively dense canopies when the laser beams could properly penetrate the canopies.

In woody areas with complex or tall canopies, it may be difficult to find ground positions for full coverage of a target canopy. Indeed, we obtained inaccurate results in canopies above 10 m, even though the method gave us accurate results under 10 m (Hosoi and Omasa, 2007). It may be possible to complement lidar measurements on the ground by using measurements from above the ground (Hosoi and Omasa, 2007, 2009). Although this can be difficult in the field, we effectively combined ground-level lidar measurements with measurements obtained by using airborne scanning lidar (Hosoi et al., 2010). The applicability of this technique should be validated by additional experiments in various locations with different species.

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