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Estimation of the leaf area density distribution of individual trees using high-resolution and multi-return airborne LiDAR data

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ABSTRACT

In this paper we demonstrate a method for estimating the leaf area density (LAD) distribution of individual trees using high-resolution airborne LiDAR. This method calculates the LAD distribution from the contact frequency between the laser beams and leaves by tracing the laser beam paths. Multiple returns were used to capture the foliage distribution in the inner part of the crown. Each laser beam is traced from a location of the last return to the location of the first or intermediate return that is recorded immediately before the last return. We verified the estimation accuracy of the LAD distribution using terrestrial LiDAR data from single trees (*Zelkova serrata* and *Cinnamomum camphora*). The appropriate voxel size for representing the LAD distribution from the airborne LiDAR data was determined to be 1 m × 1 m × 0.5 m. The accuracy of the estimated LAD distribution for this voxel size was then examined while considering the number of airborne incident laser beams on the voxel (*N*) and the return type used. When only the first and single returns were used, the LAD was overestimated even for the voxels with large *N*. LAD was estimated as zero for most voxels with small *N*, although LAD was significantly overestimated for several voxels. We found that using the last and intermediate returns improved the LAD estimation accuracy even if *N* was the same. The mean LAD estimation error was 0.25–0.3 m^2/m^3 for both species. Assigning different weights to the first and intermediate returns improved the accuracy slightly. Estimation error clearly corresponded to *N*, and *N* of 8–11 could be a criterion for an accurate LAD estimation.

1. Introduction

Trees in urban spaces have a significant influence on urban environments through solar shading, transpiration, wind breaking, air purification and soundproofing. Knowledge of the three-dimensional structures of individual trees is important for their maintenance and for understanding their effects on urban environments. The leaf area density (LAD) distribution is a key index for characterizing the vertical and horizontal crown structures and is defined as the total one-sided leaf area per unit volume.

Various ground-based indirect methods for measuring LAD distribution have been developed. The point quadrat method (Wilson, 1960, 1963) offers an accurate estimation when sufficient probes are inserted into the target canopy. Iio, Kakubari, and Mizunaga (2011) developed a three-dimensional light transfer model based on this method, which can accurately estimate the photosynthetic photon flux density distribution in a crown. However, the point quadrat method is well known to be labor intensive. Another approach is the gap fraction method, which measures transmitted light under the target canopy and is often used to estimate foliage density. One implementation of this is the LAI-2000 (LI-COR) plant canopy analyzer (Welles & Norman, 1991) that has been used in numerous studies to obtain the leaf area index (LAI). Techniques for estimating the influence of leaf clumping have also been studied (Chen, Rich, Gower, Norman, & Plummer, 1997; Ryu, Nilson, et al., 2010), but three-dimensional foliage distribution remains difficult to measure.

Recently, terrestrial light detection and ranging (LiDAR) has received much attention as a means of determining the canopy structure. Detailed tree models have been generated that reconstruct each shoot or leaf (Côté et al., 2009, 2011; Hosoi, Nakabayashi, & Omasa, 2011). High-resolution terrestrial LiDAR observation offers an accurate estimation of the LAD distribution (Hosoi & Omasa, 2006, 2007). However, it is laborious to carry out such LiDAR scans for many trees.

Airborne small-footprint LiDAR can acquire three-dimensional information of many trees at a high spatial resolution in a short time. The following methods have been established for deriving the tree geometry from airborne LiDAR data: tree height (Hyyppä, Kelle, Lehikoinen, & Inkinen, 2001; Næsset & Økland, 2002; Omasa, Akiyama, Ishigami, & Yoshimi, 2000; Persson, Holmgren, & Soderman, 2002), crown base height (Holmgren & Persson, 2004; Popescu & Zhao, 2008), and crown shape and volume (Hecht, Meinel, & Buchroithner, 2008; Kato et al., 2009; Omasa, Hosoi, Uenishi, Shimizu,

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& Akiyama, 2008). LAI estimation has also been investigated using gap fractions (Korhonen, Korpela, Heiskanen, & Maltamo, 2011; Solberg et al., 2009), regression models of LiDAR metrics (Farid et al., 2008; Jensen, Humes, Vierling, & Hudak, 2008; Riaño, Valladares, Condés, & Chuvieco, 2004; Zhao & Popescu, 2009) and the contact frequency between laser beams and foliage (Morsdorf, Kötz, Meier, Itten, & Allgöwer, 2006). Wang, Weinacker, and Koch (2008) and Sasaki, Imanishi, Fukui, Tokunaga, and Morimoto (2012) also attempted a voxel-based reconstruction of the foliage distribution. However, these studies did not consider the LAD for each voxel. Solberg, Weydahl, and Næsset (2010) used voxel-based gap fraction (laser penetration rate) distribution for simulating X-band interferometric height.

Methods for estimating LAD distribution using airborne LiDAR have been explored less thoroughly. Hosoi et al. (2010) developed a method for estimating LAD distribution by combining airborne and terrestrial LiDAR. They calculated the LAD based on the contact frequency between the laser beams and the leaves. The contact frequency was computed by tracing the path of the laser beams and counting the number of laser beams in each layer that trigger a return (laser beam interception) and those that do not (laser beam pass). An airborne LiDAR point cloud acquired by the first return mode was used, which yielded an underestimated LAD when only airborne data were used. Song, Maki, Imanishi, and Morimoto (2011) proposed a method for estimating plant area density (PAD) distribution involving the acquisition of airborne LiDAR data by employing a multi-return mode. Laser beams were traced from the points derived from only the first or single returns to avoid the multiple counting of individual laser beams.

This study aimed to develop a method for estimating the LAD distribution of individual trees using multi-return airborne LiDAR data. More specific objectives were to determine the appropriate voxel size for representing the LAD distribution by the airborne LiDAR data, and elucidate the estimation accuracy of LAD while considering the number of incident laser beams on the voxel and return type used.

2. Materials

2.1. Airborne LiDAR data

The study site was Hisaya-Odori Street in Nagoya, Japan. Hisaya-Odori Street is wide and lined with numerous broadleaved trees. A helicopter-based laser scanning system (Nakanihon Air Service) with an LMS-Q560 sensor (RIEGL) was employed for the airborne LiDAR observation. Fig. 1 (left) shows the flight track and Table 1 shows the data acquisition specifications. The flight altitude was 350 m, the footprint diameter was 0.18 m, and the distance between the consecutive footprint centers on the ground under the flight track was 0.2 m in the flight direction and 0.25 m in the scan direction. A multi-return mode was used; first, intermediate, last and single returns were obtained. The number of returns per laser shot that the sensor could obtain was unlimited. Airborne LiDAR data were acquired on September 6, 2010, during which there were leaf-on conditions in Japan.

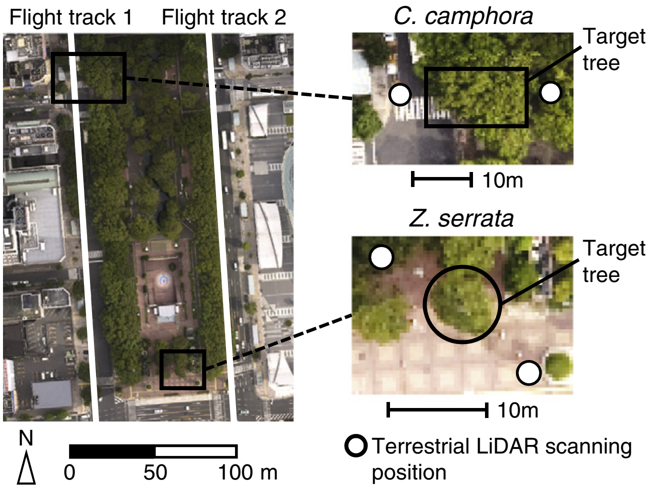

Fig. 1. Airborne LiDAR observation flight tracks, location of the trees used in analysis, and terrestrial LiDAR scanning positions.

Table 1
Airborne LiDAR observation specifications.

Date	September 6, 2010
Observation system	SAKURA (Heliborne system, Nakanihon Air Service)
Altitude	350 m
Point spacing on the ground under the flight track	0.25 m (scan direction), 0.2 m (flight direction)
Scanner	LMS-Q560 (RIEGL)
Wave length	1550 nm
Laser beam divergence	0.5 mrad
Ranging accuracy	20 mm
Range resolution	0.5 m
Number of targets per pulse	Unlimited

We selected a Japanese Zelkova (*Zelkova serrata*) and a Camphor laurel (*Cinnamomum camphora*) for analysis. These trees are common roadside species in Japan. The crown of *Z. serrata* widens toward its upper part, in which the foliage is densely distributed. *C. camphora* has an oval crown and the foliage is distributed from the upper to the lower part of the crown. The height and foliage density of the selected trees were close to the averages for these species in the study site; each tree was selected from twenty trees of that species as discerned by analysis of the variation of tree height and laser beam penetration ratio (P_{AL}) using the airborne LiDAR data. P_{AL} is given by N_p/N_i, where N_p is the number of the laser beams penetrating the tree and N_i is the number of the incident laser beams on the tree. For the *Z. serrata* and the *C. camphora*, the tree heights were 10.5 m and 15 m, the crown lengths were 7 m and 11 m, and the P_{AL} were 0.37 and 0.32, respectively.

The location of the trees is shown in Fig. 1. The *Z. serrata* was an isolated tree and the *C. camphora* was a part of a canopy. The incident zenith angles of the laser beams from flight track 1 and flight track 2 were small for the *C. camphora* (mean zenith angle: 2.5°) and the *Z. serrata*, (mean zenith angle: 7.5°) respectively. The maximum number of returns per pulse was 4 for the *Z. serrata* and 5 for the *C. camphora*. The proportions of single, first, last, and intermediate returns to all returns from the crown were 0.35, 0.41, 0.11, and 0.13 for the *Z. serrate* and 0.28, 0.41, 0.18, and 0.13 for the *C. camphora*, respectively.

The foliage density varies within a tree crown. Therefore, even if only one tree is used, the relationship between the estimation accuracy of LAD for a voxel and the number of airborne laser beams incident on the voxel (N) can be examined while considering the variation in LAD. The relationship could be general knowledge to assess the estimation accuracy based on the obtained data. Trees in urban spaces differ in crown shape and foliage density because of pruning and health conditions. Ideally, the accuracy should be verified under all these conditions, but it is impractical to do so at one time. Therefore, we used trees with average structural characteristics to ensure broad variation in the LAD and N. The influence of the difference in foliage structure and foliage distribution on the estimation accuracy of LAD distribution was examined using different tree species.

2.2. Field data acquisition and processing

2.2.1. Terrestrial LiDAR data

Field measurements were carried out on September 2, 2010. We obtained the LAD distribution using terrestrial LiDAR to verify the results from the airborne LiDAR. The selected *Z. serrata* and *C. camphora* were measured from two scanning positions using a terrestrial laser scanner