ISPRS Journal of Photogrammetry and Remote Sensing 74 (2012) 11–19

Contents lists available at SciVerse ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

journal homepage: www.elsevier.com/locate/isprsjprs

Estimation of vertical plant area density profiles in a rice canopy at different growth stages by high-resolution portable scanning lidar with a lightweight mirror

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ARTICLE INFO

Article history:
Received 30 March 2012
Received in revised form 11 July 2012
Accepted 20 August 2012
Available online 19 September 2012

Keywords:
Laser beam coverage index
Plant area density
Portable scanning lidar
Rice
Three-dimensional imaging
Voxel-based canopy profiling

ABSTRACT

We used a high-resolution portable scanning lidar together with a lightweight mirror and a voxel-based canopy profiling method to estimate the vertical plant area density (PAD) profile of a rice (*Oryza sativa* L. cv. Koshihikari) canopy at different growth stages. To improve the laser's penetration of the dense canopy, we used a mirror to change the direction of the laser beam from horizontal to vertical (0°) and off-vertical (30°). The estimates of PAD and plant area index (PAI) were more accurate at 30° than at 0°. The root-mean-square errors of PAD at each growth stage ranged from 1.04 to 3.33 $m^2\,m^{-3}$ at 0° and from 0.42 to 2.36 $m^2\,m^{-3}$ at 30°, and those across all growth stages averaged 1.79 $m^2\,m^{-3}$ at 0° and 1.52 $m^2\,m^{-3}$ at 30°. The absolute percent errors of PAI at each growth stage ranged from 1.8% to 66.1% at 0° and from 4.3% to 23.2% at 30°, and those across all growth stages averaged 30.4% at 0° and 14.8% at 30°. The degree of laser beam coverage of the canopy (expressed as index Ω) explained these errors. From the estimates of PAD at 30°, regressions between the areas of stems, leaves, and ears per unit ground area and actual dry weights gave standard errors of 7.9 g m^{-2} for ears and 12.2 g m^{-2} for stems and leaves.

1. Introduction

The plant canopy sustains important roles in cycling materials and energy through photosynthesis and transpiration, maintaining plant microclimates, and providing habitats for various species (Monteith, 1973; Jones, 1992; Graetz, 1990; Larcher, 2001). The vertical structure of crop canopies has been studied to explain characteristics such as light distribution within the canopy, light-use efficiency, yield, growth rate, and nitrogen allocation (Imai et al., 1994; Milroy et al., 2001; Takahashi and Nakaseko, 1993; Yunusa et al., 1993). It is often represented by the vertical profile of leaf area density (LAD), which is defined as the one-sided leaf area per unit of horizontal layer volume (Weiss et al., 2004). The leaf area index (LAI) is obtained as the vertical integration of the LAD values. Plant area density (PAD) and plant area index (PAI), which encompass all aboveground organs, are used instead of LAD and LAI when aboveground organs are difficult to separate.

In measuring the structure of crops, it is important to account for changes in the vertical structure with canopy growth. Stratified clipping has been used to obtain LAD and PAD (Imai et al., 1994; Milroy et al., 2001; Monsi and Saeki, 1953; Takahashi and Nakaseko, 1993). This direct method can provide accurate results, but its laborious and destructive nature does not permit repeated measurements of the intact crop structure with canopy growth. The indirect gap-fraction method is widely used for crop measurement with commercially available tools such as cameras with fish-eye lenses and optical sensors (e.g. the Li-Cor LAI-2000 plant canopy analyzer; Bréda, 2003; Grantz et al., 1993; Hanan and Bégué, 1995; Welles and Cohen, 1996). Although it allows automatic data collection and nondestructive measurement of canopy structure, the accuracy of measurement is affected by the spatial distribution of leaves and by sunlight conditions (Chason et al., 1991; Weiss et al., 2004).

In the last decade, lidar (light detection and ranging) has been emerged as a powerful tool for three-dimensional measurements of various purposes, e.g. city modeling (Pu and Vosselman, 2009), topography mapping (Webster et al., 2006), cultural heritage surveys (Pesci et al., 2012). This technology has been also utilized for structural measurements of plant canopies (Brandtberg et al., 2003; Harding et al., 2001; Holmgren and Persson, 2004; Hosoi et al., 2005, 2010, 2011; Hosoi and Omasa, 2006, 2007, 2009a,b; Hyyppä et al., 2001; Lefsky et al., 2002; Næsset et al., 2004; Omasa et al., 2000, 2002, 2003, 2007a,b; Riaño et al., 2003). Lidar can provide 3D information by calculating the distance between the sensor and the target from the elapsed time between the emission

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0924-2716/$ - see front matter © 2012 International Society for Photogrammetry and Remote Sensing, Inc. (ISPRS) Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.isprsjprs.2012.08.001

and return of laser pulses (the time-of-flight method) or from the difference in the phases of the modulation between them (phase-shift method) or by trigonometry (optical-probe or light-section methods). Airborne lidars with a large footprint (typically 10–25 m in diameter) and a large scan width have been developed for a target of forest remote sensing on large scales (Harding et al., 2001; Lefsky et al., 2002). These systems include a waveform-recording device that digitizes the power level of the entire return laser signal from canopy elements and the ground. Although they are sufficient for large scale measurement, the image resolution has been insufficient to provide detailed descriptions of canopy structure at the level of individual plants. Meanwhile, current airborne small-footprint lidar (the footprint diameter is typically 10–30 cm) has made it possible to measure canopy structures with fine spatial resolution (Brandtberg et al., 2003; Holmgren and Persson, 2004; Hyyppä et al., 2001; Næsset et al., 2004; Omasa et al., 2000, 2003; Riaño et al., 2003). The lidar system functions as a discrete-return recording device, since it only receives a single return signal or a small number of return signals from the canopy and ground. At the use of this system, there was a tendency for tree height to be underestimated when the laser pulse density was insufficient to detect the actual tree tops (<1 pulse per m^2). Recent advances in lidar technology have increased the pulse density to >10 pulse per m^2, with a pulse repetition frequency of >200 kHz, so that the probability of laser hits on the actual tops of the trees increases and the magnitude of the underestimation is reduced (Omasa et al., 2003). This type of lidar has been used for estimating the LAI values of tree species (Magnussen and Boudewyn, 1998; Morsdorf et al., 2006) and also of crops (Houldcroft et al., 2005). However, these studies mainly focused on LAI estimation rather than on the estimation of the vertical LAD or PAD profiles, because they captured insufficient information about the vertical canopy structure to estimate the latter.

Although portable ground-based nonscanning lidar has been used in several studies of vertical foliage profiles (Parker et al., 2004; Radtke and Bolstad, 2001), portable ground-based scanning lidar is now more popular for the measurement (Henning and Radtke, 2006; Hosoi and Omasa, 2006, 2007, 2009a,b; Lovell et al., 2003; Omasa et al., 2002, 2007a,b; Takeda et al., 2005; Tanaka et al., 2004; Urano and Omasa, 2003; van der Zande et al., 2006). The latter can record much 3D data quickly and nondestructively. The efficient data collection and portability of this technology are advantageous for repeated measurements of crops over time. Commonly used portable ground-based scanning lidar systems are discrete-return recording systems at which a single or a small number of return signals from the canopy are received. In addition to the system, the waveform-recording ground-based scanning lidar system has been also utilized for canopy structural measurement (Strahler et al., 2008), by which more structural information can be extracted from the internal canopy. Thus, those technologies promise to overcome the shortcomings of the conventional means of measuring the vertical structure of crops.

Recently, we demonstrated that the vertical PAD profiles of a wheat canopy at different growth stages can be measured accurately by high-resolution portable scanning lidar with a resolution of about 1 mm at a range of about 5 m through a voxel-based canopy profiling (VCP) method (Hosoi and Omasa, 2009a). Besides a wheat canopy, it is significant for the method to be applied to other crops. Rice is one of the main crops in the world and so it is important to understand the characteristics. If the VCP method is applicable to rice canopies, the resultant vertical canopy profiles would give useful information for well understanding of the characteristics. However, a rice canopy is denser than a wheat canopy, so laser penetration might be restricted. We found that a more vertical laser beam penetrates a dense rice canopy better than a horizontal beam (Hosoi and Omasa, 2012). However, this is difficult to achieve in the field, because the lidar needs to be held above the target.

We estimated the vertical profiles of a rice canopy at different growth stages using a high-resolution portable scanning lidar and a mirror oriented at different angles to achieve vertical penetration, and compared the results with direct measurements. To assess the accuracy of the PAD estimates, we investigated the relationships between an index of laser beam coverage and the errors in PAD estimates. We propose a way to estimate the dry weight of each plant organ from the resultant PAD values.

2. Materials and methods

2.1. Plant material

The experiment was conducted in 2010 in a paddy field in Ibaraki Prefecture, 40 km northeast of central Tokyo, Japan (35°56′N, 140°04′E). Rice (*Oryza sativa* L. cv. Koshihikari) seedlings were transplanted on 1 May with 30-cm inter- and intra-row spacings. Four square plots (1.2 m × 1.2 m) were established for measurements of four growth stages, on 27 May (early tillering), 17 June (late tillering), 13 July (panicle formation), and 14 August (maturity).

2.2. Lidar measurements

We used a high-resolution portable scanning lidar that calculates distances by trigonometry (a modified TDS-130L 3-D laser scanner; Pulstec Industrial Co., Ltd., Japan) to make 3D measurements of the rice canopy. The size is 640 × 263 × 175 mm and the weight is 12.0 kg. The measurable range is 3.5–10 m. The range and scan resolutions are about 1 and 2 mm, respectively, at a range of about 5 m. A rotating mount with a stepper motor and a galvano-mirror within the lidar head automate the horizontal and vertical scanning. The range of scanning angle is ±45° for horizontal and ±20° for vertical. The wavelength of the laser beam is 786 nm and the beam diameter is 5 mm at 3.5 m. The maximum laser beam output power is 30 mW (equivalent to class 3B laser product according to IEC60825-1). The data sampling rate is 1.25 ms per point.

The lidar was installed on a bund near the measurement plots (Fig. 1A). A thin-film mirror measuring 1.0 m × 1.5 m (Refex; J. Front Design & Construction Co., Ltd., Japan) was mounted above the crop (1.5 m above the ground) on rails to reflect the laser's beam down onto the canopy. Since the mirror is made of an evaporation–deposition aluminum–plastic film, at 3.8 kg it is much lighter than a glass mirror and thus it was easy to handle in the field. The mirror's reflectance is about 90% at the laser wavelength of 786 nm. Since the laser beams are reflected twice on the mirror until they return to the lidar sensor, the returning laser beam power decreases to about 80% of the power at the normal (no mirror) setting. This might cause the decrease of the number of returning laser beams detected at the lidar sensor. Then the emitted laser beam power was adjusted to the maximum (30 mW) to keep the returning beam power enough to be detected at the lidar sensor, so that the number of detected returning beams did not decrease by using the mirror.

The rails were arranged on the field horizontally along a laser beam direction of the lidar scan. The mirror could be slid along the rails at 3.3–6.9 m from the lidar, that was equivalent to 4.8–8.4 m of the beam path length from the lidar to the ground under the target canopy with reflection on the mirror when the beam direction into the canopy is vertical (see Fig. 1C). It could also pivot on its base so that the laser beam could be directed into the canopy at different angles (defined as the central zenith angle, θ_c; Fig. 1B