Short Paper

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Estimating the leaf inclination angle distribution of the wheat canopy using a portable scanning lidar

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Abstract

The leaf inclination angle distributions of wheat (*T. aestivum* cv. Norin 61) canopy were estimated at different growth stages (tillering, stem elongation, flowering, and ripening stages) by using a high-resolution portable scanning lidar. The canopy was scanned three-dimensionally by optimally inclined laser beams emitted from several measuring points surrounding the canopy and 3-D point cloud images in each growth stage were obtained. After co-registration of lidar images between different measurement positions, leaves were extracted from the images and each leaf was divided into small pieces along the leaf-length direction. Each of the pieces was approximated as a plane, to which normals were then estimated. The distribution of the leaf inclination angles was derived from the angles of these normals with respect to the zenith. Consequently, distinctive features of the leaf inclination angle distributions at each growth stage clearly emerged. The mean leaf inclination angles on 6 April, 26 April, 16 May, and 5 June were 53.9º, 45.3º, 44.3º and 56.1º respectively and the standard deviations were 19.6º, 22.2º, 21.7º and 19.5º respectively. Moreover, laboratory measurements confirmed that the mean and standard deviations of the absolute error of lidar-derived leaf inclination angles were 4.3º and 2.0º, respectively.

Key words: Crop, Growth stage, Leaf inclination angle distribution, Portable scanning lidar, Three-dimensional imaging.

1. Introduction

The Leaf inclination angle (LIA) distribution is one of the 3-D structural properties related to light distribution within the canopy and affecting the photosynthetic productivity of the whole plant (Leihner and Ortiz, 1978; Sassenrath-Cole, 1995). Due to its importance, LIA distributions have been measured in previous studies by using devices such as a protractor with a compass (Norman and Campbell, 1989), a clinometer (Gratani and Ghia, 2002) and 3-D digitizers (Sinoquet *et al*., 1998; Shibayama, 2004). These methods, however, are very laborious, meaning the measurable leaf number is limited. In particular, for crop canopies, it is important to repeatedly measure the LIA distribution over time with the growth but the laborious nature of the above conventional methods is unfavorable for repeated measurements.

Recently, a portable scanning lidar (light detection and ranging) has been utilized to obtain the 3-D structural properties of plants (Omasa *et al*., 2002, 2007; Lovell *et al*., 2003; Hosoi *et al*., 2005; Hosoi and Omasa, 2006, 2007, 2009; Takeda *et al*., 2005, 2008). This instrument can record many 3-D point cloud data of a target quickly and automatically and thus seems usable for repeated measurements of the LIA distribution of the crop canopy. However, the instrument has not yet been used to measure the LIA distribution of the crop canopy because the range accuracy and resolution of most commercially available portable lidars, which were typically one to several cm, were insufficient to capture the inclination of each leaf. Recently, we demonstrated that the LIA distribution of broad leaved canopies can be measured using a high-resolution portable scanning lidar with range resolution of about 1 mm at a measurement range of about 5 m (Hosoi and Omasa, 2007). Such a high-resolution portable scanning lidar would be also useable for the LIA distribution measurement of a crop canopy in terms of its resolution.

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In this study, measurement of the LIA distributions of the wheat (*T. aestivum* cv. Norin 61) canopy were attempted at different growth stages by using a high-resolution portable scanning lidar.

2. Materials and Methods

The experiment was conducted at an experimental farm in Ibaraki Prefecture, Japan. Winter wheat (*T. aestivum* cv. Norin 61) seeds were sown on 2 November, 2005 using 90 kg seed grain/ha and 50-cm row spacing. Four plots (1 m×1 m, see Fig. 1) were established on different four locations in the farm. Each plot was assigned to the individual measurement of different four growth stages.

A portable high-resolution scanning lidar that calculates distances based on trigonometry (a modified TDS-130L 3-D laser scanner; Pulstec Industrial Co., Ltd., Japan) was used to obtain 3-D information of the wheat canopy (Hosoi and Omasa, 2009). The lidar's measurable range is 3.5 to 10 m. The range and scan resolutions are about 1mm and 2 mm, respectively, at a measurement range of about 5 m. A rotating mount with a stepper motor and a galvano mirror within the lidar head automated the horizontal and vertical scanning. Fig. 1A illustrates an aerial view of the wheat canopy measurement by the portable scanning lidar with four measurement positions surrounding the canopy. Arrows in Fig. 1A show the directions corresponding to the central angle of the azimuth laser beam scan from each of the measurement positions. The central zenith angle of the laser beam scan was set to 57.5º by placing the lidar head at a height of 2.5 m (Fig. 1B). The central zenith angle was chosen based on the results of our previous works (Hosoi and Omasa, 2006, 2007). Based on the lidar setting, the lidar measurements were conducted under windless conditions to avoid disturbance of the canopy by wind. The measurement dates were 6 April, 26 April, 16 May, and 5 June 2006 (155, 175, 195, and 215 days after sowing [DAS], respectively), which corresponded to the tillering, stem elongation, flowering, and ripening stages, respectively.

The lidar data set for each date was composed of four point-cloud data obtained from the four measurement positions. The individual coordinate systems for these data were registered into a single point-cloud data set with a common 3-D coordinate system for each measurement date using the iterative closest-point algorithm (Besl and McKay, 1992). Subsequently, data corresponding to the individual wheat plants was extracted from the registered images at each growth stage. At the extracted data, each type of organ, i.e. leaves, stems, ears, was distinguishable due to the fine resolution of the lidar, whereupon only leaves were

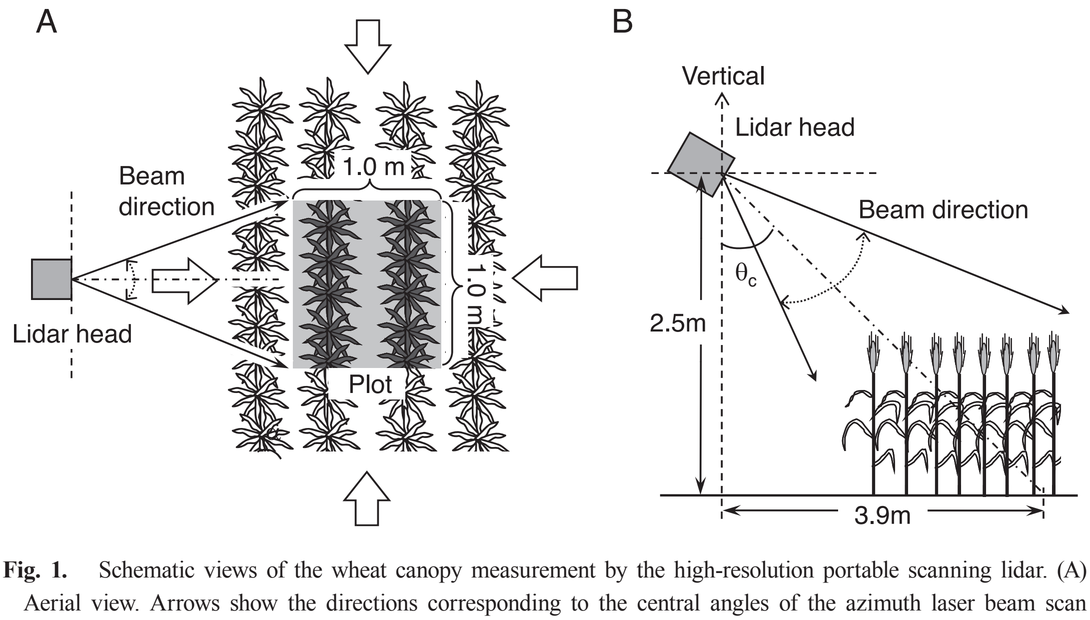

Fig. 1. Schematic views of the wheat canopy measurement by the high-resolution portable scanning lidar. (A) Aerial view. Arrows show the directions corresponding to the central angles of the azimuth laser beam scan from each of the measurement positions. (B) Side view. θ_c show the central zenith angle of the laser beams (modified from Hosoi and Omasa, 2009).

visually selected and extracted from the data. Each leaf was divided into small pieces at 15mm intervals along leaf-length directions and LIA was estimated for each of the pieces. Points within each of the pieces were fitted by a plane based on the least square method and normals to the planes were estimated. The LIA distribution was derived from the angles of these normals with respect to the zenith. Based on the procedure, LIA distribution was estimated in each of the different growth stages. To accurately estimate LIA, the interval of the pieces must be determined appropriately. LIA changes along the leaf length direction, hence the shorter interval is desirable to capture the change faithfully. However, when the interval is too short, there is insufficient lidar data to calculate LIA in each of the pieces. With these two matters in mind, the interval was determined as 15mm.

To evaluate the accuracy of the lidar-derived LIA, actual LIA values obtained by direct methods, *e.g.* the use of a protractor or clinometer, were required. However, it is very difficult to conduct direct measurements accurately in the field because the measurement takes considerable time, meaning it is difficult to maintain a stable measurement condition without wind impacting the measurement. Subsequently, an individual wheat plant was uprooted from the field at the ripening stage, placed in a pot and taken into a laboratory. 60 leaf pieces of length 15mm and width equivalent to the leaf width were randomly selected from the plant and marked to distinguish each of the leaf pieces. Lidar measurements were conducted on the plant in a setting similar to the above described field measurements, *i.e.* four measurement positions around the plant with the central zenith angle of the laser beams of 57.5º. Subsequently, LIA values corresponding to the 60 pieces were estimated using a method similar to that described above. Actual LIA values for the 60 pieces were measured by a clinometer (A-150; Shinwa Measuring Tools Corp. Japan). The error of the lidar-derived LIA was estimated by comparing lidar-derived values with actual ones.

3. Results and Discussion

Fig. 2 is a co-registered 3-D point cloud image of a wheat canopy taken on 16 May. In this image, each type of organ was distinguishable by observing the image from various perspectives.

Fig. 3 represents the LIA distributions of the wheat canopy in different growth stages, in which each angle class consists of a 5º interval. On 6 April, the distribution concentrated on the angles between 50 to 80º classes (Fig. 3A). On 26 April, a peak was observed at a 70º class, while the proportion of the lower angle classes increased (Fig. 3B). On 16 May, more even distribution was observed without clear peaks (Fig. 3C). On 5 June, the distribution shifted to higher angle classes and a peak appeared at the 65º class (Fig. 3D). The mean angles of LIA on 6 April, 26 April, 16 May, and 5 June were, respectively, 53.9º, 45.3º, 44.3º and 56.1º and the standard deviations were, respectively, 19.6º, 22.2º, 21.7º and 19.5º.

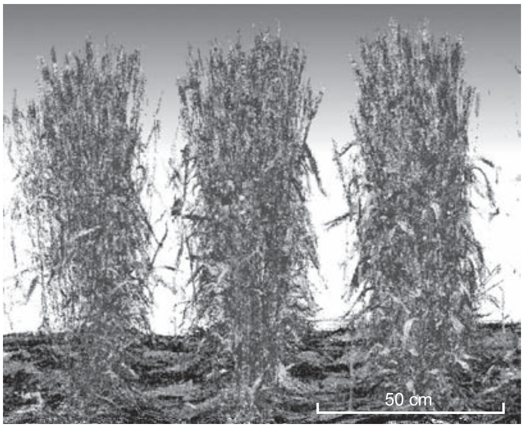

Fig. 2. A 3-D image of wheat canopy on 16 May measured by a high-resolution portable scanning lidar.

Through the laboratory measurements, it was confirmed that the absolute error of lidar-derived LIA ranged from 0.0º to 6.8º, and the mean and standard deviation of the absolute error were 4.3º and 2.0º, respectively. Those results showed that LIA can be estimated accurately using a high-resolution portable scanning lidar.

To enable accurate estimation, in the present study, measurements using the high-resolution portable lidar were conducted from four measurement points surrounding the canopy with optimally inclined laser beams of the central zenith angle of 57.5º. For the purpose of these measurements, the whole canopy could be illuminated, including internally, by full laser beams, resulting in obtaining an accurate and precise 3-D point cloud images of the whole canopy. Thanks to these high quality 3-D images, distinctive features of the leaf inclination angle distributions in each growth stage clearly emerged. During the tillering stage on 6

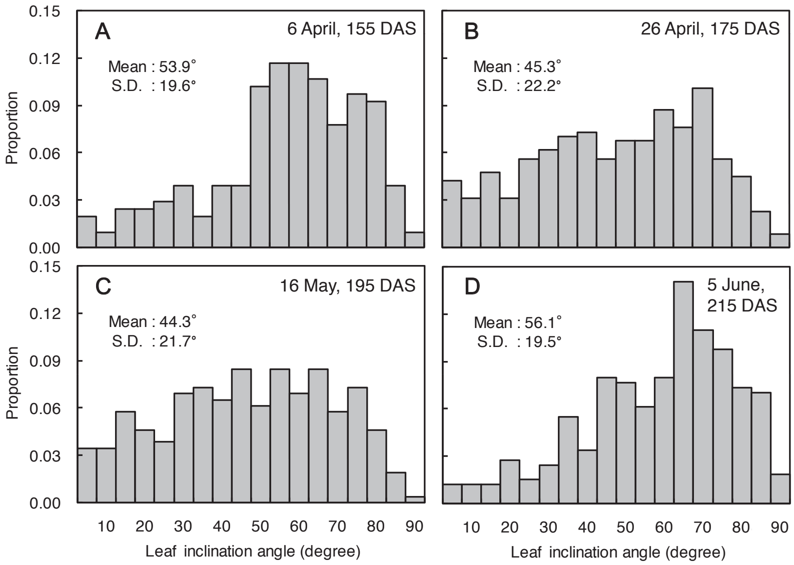

Fig. 3. Leaf inclination angle distributions in each growth stage estimated from 3-D lidar images. (A) 6 April, 155 DAS, tillering stage (n=206) (B) 26 April, 175 DAS, stem elongation stage (n=356) (C) 16 May, 195 DAS, flowering stage (n=261) (D) 5 June, 215 DAS, ripening stage (n=327). DAS, days after sowing. S.D., standard deviation.

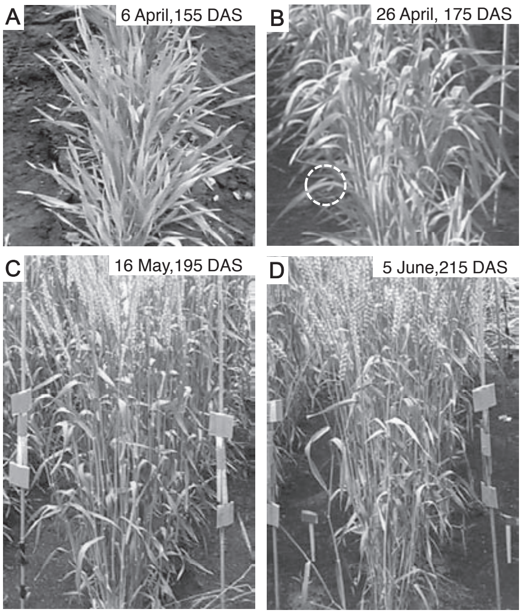

Fig. 4. Photographs of side views of wheat canopy in each measurement date. (A) 6 April, 155 DAS, tillering stage (B) 26 April, 175 DAS, stem elongation stage (C) 16 May, 195 DAS, flowering stage (D) 5 June, 215 DAS, ripening stage. DAS, days after sowing. A white dotted circle in (B) is an example of a part around a bending point.

April, the majority of leaves were growing upwards (see Fig. 4A), which explains the concentration of the distribution of LIA on relatively higher angle classes (Fig. 3A). At the stem elongation stage on 26 April, although some of leaves still grew upwards, most bent downwards from the middle of the leaf (see Fig. 4B). The part around the leaf bending point less inclined (see the part within a dotted circle in Fig. 4B), so that the proportion of lower angle classes increased (Fig. 3B). At the flowering stage on 16 May, almost all leaves bent downwards (see Fig. 4C), so that the higher angle class decreased and the distribution was equalized (Fig. 3C). At the ripening stage on 5 June, leaves drooped down due to senescence, particularly at the lower part of the canopy (see Fig. 4D), explaining the increase in the higher angle classes at this stage (Fig. 3D).

This study demonstrated that LIA distribution of wheat canopy at different growth stages can be estimated distinctively and accurately by a high-resolution portable scanning lidar. To enhance the applicability of the method, additional studies applying the present method to different growing conditions in other fields and different kinds of crops are needed. In addition, the inclination of other types of organs, such as stems and ears, affects the light environment of the canopy.

Although this study focused on the estimation of LIA using a high-resolution portable lidar, it would also be significant to apply the present method for estimating the inclination angle distribution of other types of organs.

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可搬型スキャニングライダーを用いた小麦の葉傾斜角分布計測

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要　　約

本研究では高空間分解能可搬型スキャニングライダーを用い，小麦 (農林 61 号) の葉傾斜角分布を異なる生育ステージで計測する方法を考案し，検証した。まず可搬型ライダーを小麦のキャノピーを取り囲む複数の地点に設置し，3 次元点群データを取得した。その際，レーザービーム入射角の設定も最適化し，キャノピー全体がその内部まで隈なくレーザービームに照射されるように配慮した。各地点から取得されたデータをレジストレーションした後，3 次元データに含まれる葉に相当するデータを抽出し，各々の葉のデータを長手方向に分割し，葉の小片に相当するデータを作成した。この葉の小片に相当するデータを 3 次元平面と近似し，その法線を小片毎に算出し，その天頂角より葉傾斜角分布を得た。その結果，葉傾斜角分布の各成長ステージ毎の違いを明確にとらえることができた。4 月 6 日，4 月 26 日，5 月 16 日，6 月 5 日の計測において，葉傾斜角分布の平均値と標準偏差はそれぞれ 53.9 ± 19.6°，45.3 ± 22.2°，44.3 ± 21.7°，56.1 ± 19.5°という値を示した。さらに実験室内での実験により本方法の誤差検証を行ったところ，絶対値誤差の平均値と標準偏差は 4.3 ± 2.0°という結果が得られた。

キーワード： 可搬型スキャニングライダー, 作物, 3 次元イメージング, 生育ステージ, 葉傾斜角分布