Voxel-based leaf area estimation from three-dimensional plant images

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Abstract

Leaf area is one of the most important elements of information in plant management. Leaf area is associated with many agronomic and physiological processes including growth, photosynthesis, transpiration, photon interception, and energy balance. Three-dimensional (3D) plant architecture is required for monitoring, since plants have three-dimensionally complex structures. A photogrammetric approach called structure from motion (SfM) was used for the 3D measurement. A method using the total area of a horizontal face of voxels could possibly be employed to estimate leaf area in 3D plant images. However, the leaf inclination angle of each small part, the voxel size, and misconfigured voxels in a vertical direction near leaf surfaces should be considered in the calculation. We propose a method for leaf area estimation in voxel-based models that overcomes these problems of estimation error. Using our method, the leaf area was estimated with an absolute error of 8.87%. This result was obtained by fully utilising 3D information such as voxel size and leaf inclination angle at each voxel. Moreover, our method does not involve manual operations for its construction, unlike a previous method. From the perspectives of high degrees of accuracy and automatic procedures, this voxel-based leaf area calculation method is advantageous.

Key words: Leaf area, Leaf inclination angle, Structure from motion, Three-dimensional, Voxel

1. Introduction

It is necessary to obtain information concerning the plant structure that reflects the plant status (Shono, 1995; Dornbusch et al., 2007) for accurate plant breeding and growth monitoring. The three-dimensional (3D) structure of plants has a major influence on plant functioning and microenvironments (Konishi et al., 2009). The spatially complicated 3D plant structure is related to the primary photosynthetic production, plant evaporation, water stress, plant growth characterization and so forth (Muraoka et al., 1998; Honjo and Shono, 2001; Leemans et al., 2013). A potential method for non-destructive measurement of the plant structure is through the use of image processing. However, each organ in a plant locates three-dimensionally, and it is difficult to estimate the structural parameters accurately from two-dimensional imaging. Consequently measuring 3D plant architecture is a common and well-integrated technique in plant biology and plant breeding. (Paulus et al., 2014).

A 3D scanner (LiDAR) and a photogrammetric approach called structure from motion (SfM) have been widely used to capture 3D images of plants. Using those 3D image acquisition methods, plant structural parameters such as leaf area index, leaf area density, leaf inclination angle, location, height and volume (Hosoi and Omasa, 2006, 2009, 2012; Hosoi et al., 2010, 2011, 2013; Dassot et al., 2011; Morgenroth and Gomez, 2014; Rose et al., 2015; Itakura and Hosoi, 2018a, 2018b; Zhang et al., 2018). Detailed 3D models of small plants can be reconstructed with SfM using consumer-based cameras.

Leaf area is one of the most important elements of information in plant management. Leaf area is associated with many agronomic and physiological processes including growth, photosynthesis, transpiration, photon interception, and energy balance (Rouphael et al., 2007). The use of mesh-based models is widely accepted as a well-known method for leaf area estimation after the 3D image acquisition. In the mesh-based models, a triangle is composed from a point and its adjacent two points. The triangles have to be created using the whole leaf and covering the leaf surface completely. However, it is very difficult to complete those triangles. Consequently, some holes occur that are not covered by any triangles and these have to be filled manually. For its application, the method that does not entail manual operation is necessary. Besides mesh-based 3D models, voxel-based 3D models have been used for plant 3D model analysis, and the construction of voxel-based 3D models does not entail a manual operation. In voxel-based 3D models, a geographical space is systematically decomposed into a set of cuboid volumetric elements (voxels) (Wu et al., 2013). It has been reported that using the voxel-based 3D model, leaf area density (LAD), leaf area index (LAI) and plant area density (PAD) related to leaf area can be estimated (named VCP method; Hosoi and Omasa, 2006, 2012).

In the VCP method, the LAD and PAD were calculated based on the frequency of contact between the laser beam and the canopy (contact frequency). However, instead of this, another method using the total area of a horizontal face of voxels may possibly be used. Nevertheless, when estimating the leaf area by calculating the sum of voxel number multiplying an area of a horizontal face of a voxel, each small part within one leaf contains a different leaf inclination angle. Therefore, the result of leaf area estimation is influenced by the leaf inclination angle at each small part. Additionally, the result is also dependent on the voxel size used for the estimation and the appropriate voxel size for the estimation has not yet been introduced. Moreover,
when plant 3D models are reconstructed with SfM, some points are made in the vertical direction near the leaf surface due to misconfiguration of estimated points. As a result, the leaf 3D models converted into a voxel-based model have duplicated voxels around leaf surfaces, leading to overestimation of the leaf area unless pretreatment for the redundancy is applied.

In this study, we propose a method for accurate leaf area estimation in voxel-based models that overcomes these problems which cause estimation error.

2. Materials and methods

2.1 Plant material

Small plants, namely, eggplant (*Solanum melongena*), pea (*Pisum sativum* L.), common bean (*Phaseolus vulgaris*), cucumber (*Cucumis sativus* L.), broccoli (*Brassica oleracea* var. *italica*), and cabbage (*Brassica oleracea* var. *capitata*) were selected for the experiments as shown in Table 1.

2.2 3D reconstruction of plants

The experimental flow is represented in Fig. 1. The method for leaf area calculation is explained below and with reference to Fig. 2. Initially, the plant 3D images like Fig. 2 (a) were acquired using images taken from multiple views. The camera used for the image acquisition was a Canon EOS M2 (Canon Inc., Tokyo, Japan). The fixed focal length lens used in this study was EF-M22 mm F2 STM (Canon Inc., Tokyo, Japan). It was handheld and moved in a circle around the sample. Fifty JPEG images were recorded for each sample to obtain clear 3D models. The distance from the camera to the plant was approximately 30 to 100 cm. The images were taken from oblique angles. The image resolution was 3456 × 5184 pixels. The software Agisoft Photoscan Professional (Agisoft LCC, Russia) was used for the 3D point cloud image construction using SfM (Dandois et al., 2015). The parameter for camera calibration was obtained with a checker board using the software Agisoft Lens (Agisoft LCC, Russia). Then, the calibration was conducted after choosing the image files to align with the camera parameter. The parameter for the 3D image density in both finding tie points and building dense cloud images was “high”. The average distance between the neighbouring points in the target leaf was about 0.04 cm. To assign a spatial scale and coordinates to the reconstructed 3D models, a cuboid box (13 cm × 12 cm × 9 cm) was positioned next to the plant (Miller et al., 2015). If the reference box is too small, the mis-reconstruction of the reference box leads to the scaling error. On the other hand, if the reference box is too big, only a part of the box was recorded in the original images, resulting in the mis-reconstruction of the reference in the 3D images. Thus, the scale of the reference cuboid should be determined based on the scale of the target sample to be three-dimensionally reconstructed. After the 3D reconstruction as shown in Fig. 2 (a), each leaf was segmented manually in the 3D models to estimate its leaf area (Fig. 2 (b)).

Fig. 1. Flow chart of the experiment. The flow is divided into [1] the estimation of leaf area and [2] actual measurement of leaf area.

![Flow chart of the experiment. The flow is divided into [1] the estimation of leaf area and [2] actual measurement of leaf area.](image)

Table 1. Approximate values of physical properties of the sample.

| Plant name     | Number of sample | Average leave number | Height (cm) | Length of major axis (cm) | Length of minor axis (cm) |
|----------------|------------------|-----------------------|-------------|--------------------------|--------------------------|
| Eggplant       | 60               | 5.7                   | 37.2        | 12.3                     | 7.5                      |
| Pea            | 20               | 6.7                   | 38.3        | 7.1                      | 5.1                      |
| Common bean    | 20               | 6.7                   | 23.3        | 5.3                      | 2.9                      |
| Cucumber       | 21               | 4.0                   | 13.1        | 7.2                      | 5.7                      |
| Broccoli       | 22               | 4.8                   | 13.2        | 7.0                      | 5.4                      |
| Cabbage        | 20               | 6.5                   | 12.6        | 6.5                      | 6.2                      |

Fig. 2. 3D images of leaves. Image (a) represents the reconstructed 3D model using SfM (eggplant). Image (b) is a segmented leaf. Image (c) represents voxel-based 3D model converted from image (b). Image (d) shows the distribution of leaf inclination angle at each voxel. The value of the legend is the leaf inclination angle.
2.3 Voxelization

All points constituting the 3D model were converted into voxel coordinates, in which each $x$, $y$, and $z$ values of point cloud data were rounded to the nearest voxel coordinate value (Hosoi and Omasa, 2006; Hosoi et al., 2010, 2013). Voxels corresponding to coordinates converted from points within the data were assigned an attribute value of 1 and those corresponding to the spaces without any points were given the attribute value of 0 (Hosoi and Omasa, 2006). In Fig. 2 (c), each green box (voxel) contains the attribute value 1, while the other voxels have the attribute value 0. The result of leaf area estimation using present methods is influenced by the voxel size. The leaf area was estimated using the two methods by increasing the voxel size from 0.04 cm to 0.30 cm with 0.01 cm increments.

2.4 Leaf area estimation methods

The calculation of leaf area estimation using a voxel-based 3D model was performed by multiplying the total number of voxels within a leaf by the area of the horizontal face of a voxel (Itakura and Hosoi, 2018c). However, in leaf area estimation, the leaf inclination angle, the redundant voxels in a vertical direction, and voxel size have to be considered. Voxel size is equivalent to the length of one side of a voxel. Methods using the representative inclination angle of one entire leaf as shown in Fig. 3 (a) (Method 1), or the angle at each point on the leaf (Method 2) are available to compensate for leaf inclination angles. The leaf area was estimated using each of these two methods and the estimation errors compared. First, the technique of reducing voxels in a vertical direction is referenced below, and then the two methods are explained.

2.4.1 Voxel-elimination in the vertical direction

To avoid counting redundant voxels on the leaf surface in the vertical direction, the pretreatment as described below was conducted before the leaf angle compensation. In the voxel-based 3D models, some redundant points exist in the vertical direction as shown in Fig. 3 (b), resulting in overestimation of the leaf area. Therefore, for the voxels whose $x$ and $y$ coordinates were the same, the voxel whose $z$ coordinate with the higher value was retained and the others were deleted. Thus only those voxels corresponding to the leaf surface were used and the other voxels deleted (Fig. 3 (c)).

2.4.2 Leaf area estimation method using one representative inclination angle of one leaf (Method 1)

In Method 1, the leaf inclination angle around the leaf centroid (Fig. 3 (a)) was used. Here, the centroid means the centroid in the $xy$ coordinate of the target leaf. The inclination near the leaf centroid was measured with an inclinometer and the value corresponding to the representative inclination angle of one leaf was obtained. Then, the leaf area was estimated as shown in Eq. (1) and (2). Here, a plane was fitted around each voxel to estimate the leaf inclination angle (Itakura and Hosoi, 2018c). For the plane fitting, 342 neighbouring voxels $(7 \times 7 \times 7 - 1)$ of the voxel of interest were focused on. Then voxels with the attribute value 1 in the 342 voxels and the voxel of interest were used for the plane fitting. The normal vector of the fitted plane was obtained after the plane fitting. The zenith angle corresponding to the leaf inclination angle was calculated from the vector. When the number of voxels for the plane fitting is small instead of 342 neighbouring voxels, the fitting was prone to error due to the noises (Itakura and Hosoi, 2019). On the other hand, if the larger regions are selected, the fitting is influenced by the difference of the leaf inclination angle at small area in the regions.

\[
S = (\text{voxel size})^2 \times (\text{the number of voxels}) \tag{1}
\]

\[
\langle \text{Leaf Area} \rangle = S \times \frac{1}{\cos \theta} \tag{2}
\]

In Eq. (1), $S$ is equal to leaf area projected onto xy-coordinate. 

2.4.3 Leaf area estimation method using leaf inclination angle at each voxel (Method 2)

As shown in Fig. 2 (d), leaf inclination varies from voxel to voxel. In Method 2, leaf area was estimated considering the leaf inclination angle at each voxel instead of using the angle on the leaf centroid as a representative value. In method 2, leaf area
was calculated as shown in Eq. (3).

$$(\text{Leaf Area}) = \sum_{i=1}^{n} \left\{ \text{voxel size}^3 \times \frac{1}{\cos \theta_i} \right\}$$  \hspace{1cm} (3)

where \(n\) is the number of voxels constituting the leaf and \((i=1, 2, \ldots n)\) represents the angle of the area around \(i\)-th voxel.

### 2.4.4 Evaluation of voxel size in the leaf area estimation

The appropriate voxel size for leaf area estimation is dependent on the average distance between the nearest points in the reconstructed 3D models. The average distance between the nearest points of the 3D models was calculated before the conversion into voxel-based 3D models. Then, V. Size/D (Voxel Size per Distance; ranging from 1 to 3), representing the voxel size per the average minimum distance between points in the target leaf was defined. This value is derived by dividing the voxel size (unit: cm) by the distance (cm), thus the value has no units. We examined at what value of V. Size/D, the leaf area estimation error attained its minimum value. The investigation was conducted on all six samples.

### 2.5 Evaluation of leaf area estimation

To calculate the accuracy of leaf area estimation using Methods 1 and 2, the actual value of the leaf area and the estimated leaf area using those methods were compared (Eggplant: 60, Pea: 20, Common bean: 20, Cucumber: 21, Broccoli: 22, Cabbage: 20 leaves). To obtain the actual leaf area, the leaves in the plant samples were cut down manually and JPEG images of the leaves were captured. The areas were calculated by multiplying the number of pixels by the area per pixel. The leaves were pressed between a transparent board and white board to flatten them while taking the JPEG images. JPEG images are saved with non-reversible compression, although the compression rate is significantly small, and it is considered that the measurement error in the image acquisition is also significantly small.

Next, for leaves in which the fluctuation of leaf inclination angle is greater, leaf area estimation was conducted. The standard deviation of leaf inclination angle in each leaf was calculated for all leaves, and then the 30 leaves having the highest values were selected. The estimation error of their leaf areas using Methods 1 and 2 were compared.

### 3. Results

Table 2 shows the estimation error of leaf area (mean absolute error: MAE) with Methods 1 and 2. The estimation errors of Method 1 and Method 2 were 10.01% and 8.87%, respectively. The estimation error from Method 2 is lower than that from Method 1 for all samples. There is a significant difference between the absolute error in Method 1 and that in Method 2 \((p < 0.05)\). In Method 2, there is not a big difference in the value V. Size/D, as it ranged only from 1.6 to 2.1.

When leaf area was estimated by multiplication of the total number of voxels within a leaf by the area of the horizontal face of a voxel, without the compensation of leaf inclination angle and the voxel reduction in the vertical direction as mentioned in section 2.4.1, the average leaf area estimation error (MAE) in all samples was 17.68%. As shown in Fig. 3 (b), some voxels exist in a vertical direction and this leads to overestimation of leaf area. On the other hand, as represented in Fig. 3 (c), the estimation may be improved by merging some voxels in a vertical direction into one point. However, the average estimation error in all samples was 13.6%, worse than that with Methods 1 and 2. Because this estimation is equal to calculation the projected area into xy-coordinate and it does not consider the inclination of leaves, resulting in the underestimation.

Fig. 4 illustrates a typical example of the relationship between V. Size/D and the absolute error of leaf area estimation. Fig. 4 (a), (b) and (c) represent the leaf top view images whose V. Size/Ds are approximately 0.5, 1.7 and 3.0, respectively. In Fig. 4 (a), the

Table 2. Estimation error of leaf area estimation with Methods 1 and 2. The error is calculated based on mean absolute error (MAE). V. Size/D represents the value of the appropriate voxel size for leaf area estimation per average minimum distance between points in 3D models. The bottom row shows the estimation error of curved leaves in which the standard deviation of leaf inclination angle is larger.

|                | Method 1 |    | Method 2 |    |
|----------------|----------|----|----------|----|
| V. Size/D      | Absolute error (%) | V. Size/D | Absolute error (%) |
| Eggplant       | 10.60    | 1.7| 9.65     |
| Pea            | 9.40     | 1.7| 8.33     |
| Common bean    | 12.48    | 1.6| 12.10    |
| Cucumber       | 7.99     | 2.1| 6.54     |
| Broccoli       | 8.41     | 2.0| 7.66     |
| Cabbage        | 11.20    | 2.1| 7.65     |
| all samples    | 10.01    | 1.9| 8.87     |
| Curved leaves  | 12.69    | 2.0| 10.68    |

Fig. 4. A typical example of the relationship between V. Size/D and absolute error of leaf area estimation. Images (a), (b), and (c) represent the leaf top view images whose V. Size/Ds are approximately 0.5, 1.7, and 3.0, respectively. V. Size/D represents the value of the appropriate voxel size for leaf area estimation per average minimum distance between points in 3D models.
voxel size is so small that many holes can be observed on the leaf, while in Fig. 4 (c), the voxel size is large and the leaf edge roughly described. Consequently, the most accurate estimation is in Fig. 4 (b). Leaf area estimation was conducted for 30 leaves whose fluctuation of leaf inclination angle in each leaf is greater. The average standard deviation of leaf inclination angle at each voxel in one leaf was 14.6 and the MAE of the leaf area estimation with Methods 1 and 2 was 12.69 % and 10.98 %, respectively. The relationship between the leaf area estimation error and its leaf inclination angle is defined below. When the leaf inclination of an entire leaf exceeds 40, is between 20 and 40, or is less than 20, on average the respective mean absolute estimation errors are 11.5 %, 9.45 %, and 8.56 %.

4. Discussion

Whether the holes occur due to voxel size is dependent on the distance between the nearest points in the 3D model before conversion into voxel-based 3D models. Therefore, the appropriate voxel size should be determined based on V. Size/D which takes into account distances in the model. In this study, the optimum value of V. Size/D where voxel size is neither too small nor too big was around 2. It is suggested that the V. Size/D of about 2 would be the appropriate value for precise leaf area estimation.

In Method 2, leaf area is estimated considering the leaf inclination angle at each point on the leaf. For example, the leaf inclination angle in the lower area around the leaf tip shown in Fig. 2 (d) is higher than that in the center area. In some leaves with comparatively greater leaf curvature, the inclination angle differs significantly within an individual leaf. In Method 2, the compensation for leaf inclination at each voxel on the leaf is included. Therefore, the estimation error is lower than that with Method 1 in which a representative inclination angle from one leaf was used. The estimation accuracy is also influenced by the estimation error of leaf inclination angle. However, the absolute angle estimation error is less than 2 degree (Itakura and Hosoi, 2018c). Thus, the influence of the angle estimation error on the leaf area estimation is not so significant. By adopting Method 2, the leaf area estimation accuracy was improved. Moreover, Method 2 utilises the angle at each point. Thus the method is applicable to the leaves in which the fluctuation of leaf inclination angle is comparatively greater as mentioned earlier in the result section. Using Method 2, leaf area estimation can be done to leaves that are bent. It is implied that this method is advantageous for withering leaves and that the monitoring will lead to precise plant management.

Also, with lower leaf inclination angles of the target leaves, the estimation error tended to decrease. However, there is no significant difference among leaves with different inclination angles. Even if the leaf has a steep inclination angle, the estimation error is about 10 % and it would not present a major problem for the application.

The average of leaf area estimation error with Method 2 was 8.87 % in all samples. With respect to accuracy in phenotyping, errors between 5 and 10 % are acceptable (Paproki et al., 2012). The method proposed in this study fully utilises the 3D information such as voxel size and leaf inclination angle at each voxel, leading to the high degree of accuracy. In some cases, the leaf area estimation within 10 % error could not conducted as the error with common bean was about 12 %. This would be due to the mis-reconstruction of the plant materials due to its structural complexity. However, the optimization of the number of images and the camera angle to the sample will lead to the enhancement of the estimation accuracy. Therefore, as a future work, the optimization of the whole experimental setup including them should be considered.

From the perspectives of high degrees of accuracy and automatic procedures, this voxel-based leaf area calculation method has major advantages. It could be helpful in various situations such as in conducting effective plant breeding, crop yield estimation, and development of new cultivars by phenotyping.

Acknowledgment

Funding: This work was supported by ACT-I, Japan Science and Technology Agency.

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