Precise and continuous measurement of plant heights in an agricultural field using a time-lapse camera

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Abstract

Plant height is an important trait linked to yield potential and phenotyping; hence, a method for measuring plant height with sufficient temporal and spatial resolutions is required. Furthermore, a low-cost and easy-to-use method is desirable for practical application in agricultural fields. In previous studies, methods for measuring plant height have only fulfilled one or a few of these requirements, and there have been very few studies that have attempted to fulfill all the above requirements in one method. The current study proposes a low-cost plant height measurement system using a commercial time-lapse camera to capture seasonal and year-to-year variations in plant height that represent plant heights at the site scale. The system’s performance was tested in a rice field in Japan for two growing seasons. Plant heights were determined to the nearest 1-cm in height from the camera images by referencing a scale bar that was erected next to the four target plants. The obtained plant heights were corrected for vertical distortion (referred to as the ‘displacement effect’ in the main text), and those were compared with the direct height measurements for each the target plant and site-scaled plant heights that were averaged from 10 samples. For both cases, good agreement between the captured and referenced plant heights was obtained. The system was able to reflect detailed seasonal variations in the plant heights including the maximum heights and the times at which they occurred as well as year-to-year differences. Consequently, the developed system appears to fulfill all the necessary requirements for practical measurement of plant height on-site in agricultural fields.

Key words: Border effect, Crop height, Phenotyping, Plant growth, Rice

1. Introduction

Plant height in agricultural fields is linked to yield potential (Cornelissen et al., 2003; Tackenberg, 2007; Tilly et al., 2014) and, thus, investigations into this trait are attracting increasing interest in studies of plant phenotyping (Hartmann et al., 2011; Araus and Cairns, 2014; Li et al., 2014) and simulations of crop growth models (Breuer et al., 2003; Confalonieri et al., 2011; Tilley et al., 2014, 2015). These and other investigations have emphasized the importance of precise resolution for plant height measurements on the millimeter or centimeter scale (Hartmann et al., 2011; Friedli et al., 2016, Nguyen et al., 2016) and frequent or continuous measurement throughout the crop growing season (Confalonieri et al., 2011; Araus and Carins, 2014; Sritarapipat et al., 2014).

The direct method for measuring plant height is simple: measure the distance from the ground to the top of a plant using a measuring tape or scale. However, the direct method requires conducting frequent measurements to identify seasonal variations and estimate representative averages because crop growing seasons are often short. Indeed, some crops need only 3 months from sowing/transplanting to harvesting. This requirement is labor intensive and time-consuming. To overcome this obstacle, several different methods have been proposed using current, advanced technology.

One simple and common approach to measuring plant height is the visual obstruction method (Robel et al., 1970). This method uses a standardized tool called the Robel pole, which is 150 cm tall and 3 cm in diameter, with alternating color markings every 10 cm. The Robel pole is erected at the sampling site and then plant height is estimated by visually observing the highest color band on the Robel pole that is completely obstructed by the plant. The visual obstruction method is quick and enables easy estimation of plant height. However, there are two issues with this method. First, the method still requires visiting the field for measurements, which is laborious and time-consuming when frequent or continuous measurement is needed. Second, the measurement area is limited because of the narrow diameter of the Robel pole. Hence, this method has been modified to incorporate the use of a board or sheet with a scale on it to extend the measurement area (Zehm et al., 2003; Limb et al., 2007). This modification enables measuring a larger area, but it is not suitable for continuous measurements in situ for the following reasons: it would be difficult to maintain the board or sheet in situ (i.e. outdoors) continuously; and, even if the board or sheet could be maintained continuously, it would disturb the local environment in ways that could affect plant growth (e.g. by changing the amount of radiation that reaches plants or obstructing the flow of wind). To accommodate frequent or continuous measurement, film or digital cameras have been incorporated into plant measurement systems to capture images frequently over long periods (Sritarapipat et al., 2014; Constantino et al., 2015). The limited measurement length and resolution of the Robel pole has also been improved upon by modifying its length and marking interval frequency or using another pole or scale appropriate to the study site conditions and target plant (Barkman, 1988; Zehm et al., 2003).

In more complex approaches, plant heights are estimated...
using a light-field camera that can take images with different focal planes (Schima et al., 2016) or by using a laser beam to determine the distance to the plant from a sensor (Tilly et al., 2014; Friedli et al., 2016). In other studies, an ultrasonic sensor or a camera has been mounted on a land vehicle (Andújar et al., 2012) or an unmanned aerial vehicle (Anthony et al., 2014) to estimate plant heights at the site scale level.

The methods proposed in each of the above studies have several advantages. However, there is no single method thus far that satisfies all of the requirements for a system to practically measure plant heights in outdoor agricultural fields. These requirements are summarized as follows:

1. The system has sufficient temporal resolution to capture seasonal variation in plant heights using an appropriate time interval for measurements that can produce daily averages and standard deviations, without resulting in frequent data gaps due to lack of monitoring, and is able to carry out measurements over multiple years.

2. The system has sufficient spatial resolution to detect plant height on the vertical plane in a range from several centimeters to meters (to represent plant growth from sowing/transplanting to harvesting) with ca. 1-cm height resolution, is able to incorporate potential for error, and can represent site-scaled plant heights in the horizontal plane.

3. The system does not require special skills to use instruments and carry out data handling (e.g. complex image analysis) nor does it require frequent managing and maintenance to carry out measurements over multiple years or the high initial costs demanded by most laser-scanning methods.

This study aims to develop and propose a plant height measurement system that fulfills the above requirements by employing a commercial time-lapse camera, and investigates the features of the system using data obtained from a cultivated rice field. Section 2 presents details about the study site and experimental crop as well as the developed plant height measurement system, which is based on a similar concept to that of the visual obstruction method mentioned above. Errors in plant height data owing to conversion from three-dimensional plants into captured images are estimated in Section 3. Section 4 describes the results; that is, a comparison of the captured plant heights and directly measured and site-scaled plant heights. Section 5 discusses the features of the system and possible errors. Finally, the conclusions are provided in Section 6.

2. Study site, experimental crop, and plant height measurement method

2.1 Study site and experimental crop

The experiment site was a rice field located in Tsukuba, Ibaraki, Japan (36°03′ N, 140°01′ E, 11.2 m a.s.l.). The site is one of the AsiaFlux regional research network study sites (part of the FLUXNET), which was established in 1999. Meteorological data and ecological characteristics such as plant height, leaf area, and biomass have been monitored at the site since 1999 (Ono et al., 2013). A rectangular plot of 100 × 54 m was cultivated with ‘Koshihikari’ rice (Oryza sativa L.) using established methods. Further details of the site and experimental crop are given in previous studies (Miyata et al., 2005; Saito et al., 2005; Mano et al., 2007; Ono et al., 2008, 2013, 2015). Data were obtained during two rice growing seasons (2011 and 2012). The dates of transplanting and harvesting were May 5th and September 10th in 2011, and May 2nd and September 12th in 2012, respectively, with planting densities of 16 (2011) and 15 (2012) plants per m².

2.2 Plant height measurement method

2.2.1 Plant height measurement system

A weatherproof time-lapse camera (PlantCam, Wingscapes, Alabaster, AL, USA) was used to capture images of rice plants at the site. The camera has a 4.0 megapixel CMOS sensor and the 35-mm-equivalent focal length is 45 mm (lens field of view of 52°). The focus distance was set to 3 ft to infinity and the photo resolution was set to a high resolution of 2560 × 1920 pixels.

The camera was installed at a height of 64 cm (length from the ground to the center of camera lens) with a handmade plate holding a level (Fig. 1) to check and ensure that the camera remained level on the horizontal plane. The camera was pointed north-east to capture images at a right angle to the crop rows and to avoid capturing images against the sun. The distance from the camera to

Fig. 1. The plant height measurement system installed at the study site (for details see the main text).

Fig. 2. Example of an image captured by the camera that was taken at 12 p.m. on June 6th, 2011.
the target rice plants was 280 cm, and the rice plants in between the camera and target plants were removed. In this configuration, four rice plants were fully captured in each image, and those plants were numbered 1, 2, 3 and 4, from left to right (Fig. 2). To distinguish target plants from others in the background, the visual obstruction method uses either the scale bar (or pole) itself (Robel, 1970; Vermeire and Gillen, 2001; Sirirapatpat et al., 2014), or the board (or sheet) of ca. 1 × 1 m (Zehm et al., 2003; Limb et al., 2007). However, those materials were not suitable for the objectives of this study because the width of the scale bar was too narrow to cover the space occupied by the four target rice plants and a board would have disturbed the local environment and it would have been difficult to maintain the board in position during the entire measurement period. Therefore, a 123 × 110 cm white wire net that was sufficiently wide to cover the space and did not create any disturbances (i.e. as a white wire net, it had little area to absorb and emit or reflect radiation, and created negligible obstacle to wind flow) was employed, and placed behind the target plants. As a reference for determining the plant heights, a 150 cm-long scale bar with 0.5-cm interval markings was erected next to the target rice plants. The power supply for the camera comprised four AA batteries, which were placed inside the camera body, and an external AC power source converted to DC via an AC-DC converter. Thus, continuous images could be collected even in the event of power failure. The above system was installed at the site 4 days (2011) and 13 days (2012) after transplanting, and measurements were carried out until September 10th, which was the harvest date in 2011 and 2 days before harvest in 2012.

### 2.2.2 Determine plant heights from images

The camera was set to record five images per day at 3-hour intervals from 6 a.m. to 6 p.m. Each high-resolution image covered the area from the ground to ca. 140 cm in the vertical direction at the location of the scale bar. Plant heights were determined to 1-cm resolution from images by drawing a horizontal line from the highest point of the target rice plant crossing the scale bar using drawing software and identifying the nearest marking on the scale bar to this line. Five plant heights were recorded daily for each of the four target rice plants except during rainy and/or foggy periods. The daily average and standard deviation of each plant were calculated and expressed as $PH_i$ for the $i$th plant ($i = 1$ to 4). Assuming that $PH_i$ is correctly estimated (cf. section 4.2), the averaged plant height ($PH_{ave}$) for ca. 100 cm in the horizontal direction (i.e. one row with four rice plants at intervals of ca. 25 cm) and its standard deviation were calculated.

To confirm whether there was an effect of different observers on the determination method, the process outlined above was carried out by two different undergraduate students (who are not the author of the current paper), using data collected in 2014 and 2015.

### 2.2.3 Reference plant height measurement for target rice plants and site-averaged reference plants

The plant heights of the target rice plants were directly measured approximately once every ca.2 weeks. Additionally, on each measuring day, the site was divided into ten sections and one rice plant in each section was selected to provide a reference plant height at the site scale. The heights of those ten selected plants were used to calculate the site-averaged plant height ($PH_{site}$) and its standard deviation. For both the four target plants and the selected site-averaged reference plants, plant heights were manually measured to the nearest 0.5 cm using measuring tape.

### 3. Effect of displacement between the plants and the scale bar

Though the positions of the camera and the scale bar were fixed during the measurement period, the portion of the plants measured changed as a result of factors such as stem growth and changes to the highest leaf position due to strong winds or other factors. To evaluate whether there was an effect of displacement between the measured points and the scale bar on height measurements, the author tested this relationship using the schematic of the system illustrated in Fig. 3.

With the X-axis representing the ground and the Y-axis representing the scale bar at the origin (O), the camera lens is positioned at $X = L$ and $Y = h_c$. If a straight-shaped material with a true height of $h_i$ is erected at the origin, its height as measured from the scale bar, which is depicted as the dotted line in Fig. 3, must match the $h_i$. However, when the material moves $\delta L$ along the X-axis, the measured height in the image according to the scale bar ($h_{m}$) will be different from $h_i$. The difference between $h_m$ and $h_i$ is determined by the equation $h_{m} - h_{i} = \delta L \tan \alpha$, where $\alpha$ is the degree shown in Fig. 3. Then, $\tan \alpha$ is calculated as $(h_{i} - h_{c}) / (L - \delta L)$, which leads to equation (1).

$$h_{m} - h_{i} = \delta L (h_{i} - h_{c}) / (L - \delta L)$$  (1)

To confirm the validity of equation (1), an indoor experiment was conducted. The system configuration was set up identically to that in the field experiment: the camera was located at $L = 280$ cm and $h_c = 64$ cm with respect to the origin where the scale bar was placed. Then, two materials with heights of 5 and 120 cm were placed at $\delta L = -10, -5, 0, +5$ and +10 cm and captured by the camera. The materials' heights were determined from the captured images to the nearest 0.5 cm by referencing the scale bar.

![Fig. 3. Schematic drawing of the plant height measurement system in the side view.](image-url)
Then, the measured heights were plotted in Fig. 4 according to equation (1). The measured data generally agreed with the results of equation (1), but, for \( h_l \) of 120 cm, the measured height was always overestimated. This bias may be attributable to lens distortion (Laikin, 2006), and the relationship demonstrated in Fig. 4 should be interpreted considering the potential influence of both the displacement effect and lens distortion. However, because the differences between the measured data and results of equation (1) were small (i.e. close to the measurement resolution of the indoor experiment) the effect of displacement between the rice plants and the scale bar was assumed to follow equation (1) hereafter.

In the field experiment, only the stem growth of rice plants was considered to cause the displacement effect. Given that the highest leaf is positioned at the edge of the rice plant stem, \( \delta L \) can be calculated as a half of its stem diameter. The stem diameter of the rice plant was determined by referencing the scale bar, assuming that vertical length indicated by the scale bar in the images would be equal to horizontal length in the images. Future studies could determine stem diameter in images by placing a horizontal scale just above the water or ground surface near to the target rice plants; however, this method was not applied in the current study. Once the \( \delta L \) is estimated, the true rice plant height \( (h_t) \) can be calculated using equation (2), which was obtained by rearranging equation (1) and inputting the measured plant height \( (h_m) \), the height of the camera \( (h_c) \), and the distance between the camera and the target rice plant \( (L) \).

\[
h_t = \frac{(L - \delta L) \cdot L}{L} h_m + \frac{(\delta L \cdot L)}{L} h_c
\]

(2)

In the following section, values of \( h_t \) as calculated by equation (2) are used for the rice plant heights.

4. Results

4.1 Time needed for data analysis, percentages of available plant height data, and the effects of having different persons carry out data processing

Though the time needed to determine the height of the four target plants in one image depended on the rice growing stages and shapes of rice plants, each image took 1 to 4 minutes. If an average of 2.5 minutes per image is assumed, then the processing time will be ca. 12.5 minutes for one day (five images per day) and approximately 20 to 30 hours for one rice growing season with ca. 120 – 150 days.

Because water droplets adhered to the camera lens during rainfall and fog events, certain areas of some images were blurry and it was impossible to determine the plant height from them. Thus, the percentages of available data for each target plant ranged from 64% to 91% with averages of 81% (2011) and 84% (2012), as shown in Table 1. Although the percentage of available data was relatively low in a few cases (e.g. 64% for \( PH_1 \) in 2011), there were only 3 days for which no plant height data were available (2 days for \( PH_1 \) in 2011 and 1 day for \( PH_4 \) in 2012). This was because the measurement system captured five images per day and at least one image was available each day except for the aforementioned 3 days.

The plant heights were determined by two undergraduate students, taking almost the same amount of time as the author. The heights determined by the students were compared with the directly measured plant heights. The relationships between the two sets of measurements (figures not shown) are very similar to the results shown in Fig. 5(A) and Table 2 with slopes of 0.9 to 1.05, intercepts of –1.19 to 3.61 cm, coefficients of determination \( (R^2) \) of 0.98 to 1.00 in linear regression analysis, mean absolute errors \( (MAE) \) of 1.6 to 5.0 cm, and root mean squared errors \( (RMSE) \) of 1.9 to 7.2 cm.

4.2 Comparing plant heights determined from images and directly measured heights

The rice plant heights determined from images showed considerable seasonal variation, and data for \( PH_3 \) in 2011 are presented in Fig. 5(A) as an example. Overall, \( PH_3 \) increased slightly until mid-May with values of ca. 10 – 15 cm, rose continuously to a maximum of ca. 120 cm in early August, and then gradually decreased until harvest, when heights varied between ca. 100 and 115 cm. From a short-term perspective, \( PH_3 \) experienced temporary decreases, for example, in late May and early September, owing to bending of the rice plants in strong winds. Furthermore, in the later part of the rice growing season, \( PH_3 \) varied more frequently because parts of the mature rice plants were easily distorted or fell as a result of wind or the heavier weight of leaves and panicles.

The reference plant heights that were directly measured at approximately 2-week intervals followed the same seasonal trends, as shown for \( PH_3 \) in Fig. 5(A). The directly measured heights
are compared with those determined by images for $PH_3$ using a scatter plot in Fig. 5(B). The two data sets matched well, and linear regression analysis showed a slope of 1.04, an intercept of $-2.53$ cm, and a high $R^2$ of 0.99. The results of the linear regression analysis for all the sample plants are summarized in Table 2, which shows that the slopes and intercepts were close to unity (0.97 to 1.07) and around zero ($-2.53$ to $+1.90$ cm), respectively, with high $R^2$ values (0.99 to 1.00). To evaluate statistical performance, MAE and RMSE were calculated and are shown in Table 2. Both MAE and RMSE had relatively low values of ca. 2 to 5 cm, except for $PH_2$ in 2012. Interannual variation was not evident in either measure of error. For $PH_2$ in 2012, the difference between MAE and RMSE was large compared with those for other years and variables, indicating that the presence of a small number of large errors may have been caused by the mature rice plants, which had higher values for plant height, during the late period of the rice growing season. The results of the linear regression and values for error in Fig. 5(B) and Table 2 show good agreement between the datasets. These results lead us to conclude that the plant heights determined from the images represent the directly measured plant heights well.

4.3 Comparing the averaged heights of target plants with those of site-averaged plants

Figure 6(A) shows the seasonal variation in the averaged heights of the target plants ($PH_{ave}$) and the site-averaged reference plant heights ($PH_{site}$) for 2011 and 2012. The overall seasonal trends in $PH_{ave}$ for both years showed similar seasonal variation patterns to that of $PH_3$ in Fig. 5(A). $PH_{site}$ basically followed the same curve as $PH_{ave}$ except for the last two data points representing relatively large standard deviations (see the error bars) in 2011. The cause of this discrepancy and, thus, the large standard deviations for $PH_{site}$, is that two of the plants from the 10 samples had extremely short heights because of lodging. During the late period of the rice growing season, rice plants were easily bent or flattened by strong winds and/or heavy rains owing to the top-heavy structure of the rice plant (i.e. mature panicles and stalks). Thus, the differences between the values are expected to be large and result in relatively large standard deviations compared with those from the early to middle periods of the rice growing season. According to the continuous data of

![Fig. 5](image_url)

**Fig. 5.** (A) Seasonal variations in rice plant heights for $PH_3$ in 2011 according to values determined from images and those measured directly. Data determined from images for $PH_3$ represent the daily averages and their standard deviations (shown as error bars), whereas the directly measured plant heights represent one data point per day. (B) Relationship between the determined and directly measured plant heights for $PH_3$ in 2011. The linear regression results are presented as a dashed line, and the 1:1 line (solid line) is provided for comparison.

<table>
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<th>$PH_1$</th>
<th>$PH_2$</th>
<th>$PH_3$</th>
<th>$PH_4$</th>
<th>$PH_1$</th>
<th>$PH_2$</th>
<th>$PH_3$</th>
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<td>Slope</td>
<td>1.04</td>
<td>1.07</td>
<td>1.04</td>
<td>0.99</td>
<td>0.97</td>
<td>0.98</td>
<td>0.97</td>
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<tr>
<td>Intercept</td>
<td>-1.28</td>
<td>-2.11</td>
<td>-2.53</td>
<td>-1.25</td>
<td>-0.05</td>
<td>1.42</td>
<td>1.90</td>
<td>1.02</td>
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<tr>
<td>$R^2$</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
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<tr>
<td>MAE</td>
<td>3.7</td>
<td>3.3</td>
<td>2.9</td>
<td>2.8</td>
<td>3.3</td>
<td>4.5</td>
<td>1.5</td>
<td>2.0</td>
</tr>
<tr>
<td>RMSE</td>
<td>4.9</td>
<td>5.3</td>
<td>4.2</td>
<td>3.7</td>
<td>4.3</td>
<td>8.1</td>
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PHave, the maximum plant height and the time at which it occurred were appropriately detected, as seen in Fig. 6A. In contrast, from the ca. 2 week-interval data of PHsite, the maximum plant height and the time at which it occurred would be likely to be missed, especially in the case of 2011 because the plant height reached its maximum at the time between the measurement points of PHsite. A between-year difference in rice growth was also detected. That is, PHave in 2012 had lower values than PHave in 2011 starting in late June, and this difference of ca. 5 to 20 cm was retained till the end of the measurement period.

The relationship between PHsite and PHave in 2011 and 2012 are shown in Fig. 6B. The data points fell close to the 1:1 line and linear regression analysis resulted in slopes of 1.07 and 1.03, intercepts of 0.62 and 3.53 cm, and R² values of 0.95 and 0.99 for 2011 and 2012, respectively. If the two fallen rice plants with particularly low heights in 2011 i.e. the two data points with large error bars in Fig. 6A are removed from analysis, the resulting slope, intercept, and R² values become 1.05, 2.1 cm, and 0.99, respectively. The close correspondence between PHsite and PHave indicated that the plant heights averaged from the images were in good agreement with the site-averaged plant heights, even though the target plants only represented a line of ca. 1 m (width of a single row) in comparison with the total plot size of 100 × 54 m.

5. Discussion

5.1 Specific features of the developed plant height measurement system

5.1.1 Temporal resolution

The developed plant height measurement system, which is based on the concept of the visual obstruction method, was able to determine daily averaged plant heights and their standard deviations and assess the plant height during the full period of crop growth and its interannual variations. Thus far, most methods using the visual obstruction method in outdoor fields, rather than indoor settings such as plant factories (Hartmann et al., 2011; Li et al., 2014), have not been carried out continuously. In other words, measurements were only taken sporadically (Zehm et al., 2003; Limb et al., 2007). Sritarapipat et al. (2014) employed a similar approach to that of the current study by measuring plants in a rice field using a scale bar and imaging processing (band selection, filtering and thresholding). They acquired one plant height data point per day, meaning that the daily averages and standard deviations could not be calculated. The authors stated that their measurements may have been inaccurate or unreliable during rainfall events. This discrepancy may have resulted from the relatively long distance between the camera and the scale bar — in that study, the length of the scale bar in the image
comprised about one-third the vertical length of the image, meaning that even small water droplets on the lens could mask the scale bar. The short length of the scale bar in the images in that study also meant that the scale bar was not able to cover a wide range of plant heights. That is, it was difficult to apply their method for a long period of crop growth. Thus, Sritarapipat et al. (2014) only reported heights from 77 cm to 119 cm for the target rice plants in their study.

Other studies using laser-scanning techniques have achieved sufficient temporal resolution to detect changes in plant heights even over the course of a few hours. For example, Friedli et al. (2016) used a 3D laser scanner to measure maize canopy height to the nearest millimeter, and found that canopy height growth was correlated with temperature changes within a day. Though the laser-scanning method can determine plant heights with high height resolution, it has a relatively high cost and it is difficult to apply for frequent or continuous measurement in outdoor fields owing to the instruments’ characteristics (e.g. time needed for set-up and removal, limited operating temperature and humidity, and tendency to work poorly under certain weather conditions such as heavy rain and lightning), which might be disadvantageous for practical use.

5.1.2 Spatial averaging and height resolution

One important advantage of applying the visual obstruction method in agricultural fields is the relative ease of spatial scaling up of measurements at a point to the entire field because plant heights in agricultural fields are considerably more uniform than those of wild plants. Indeed, the developed system estimated ca. 1 m averaged plant heights for the four target plants to the nearest 1 cm in height, and confirmed that the target-averaged plants represented the heights of the site-averaged plants well. Furthermore, the difference in the seasonal variation of plant heights between years, which may have resulted from differing weather conditions, was also detected by the developed system. The length of the row used for the target plant averaging could be extended to ca. 2 m (i.e. eight target rice plants could be used) with the same configuration. However, the extended length of the row used for averaging affects the number of plants that need to be removed in front of the camera, which may increase the border effect discussed in Section 5.3.

The averaging scale and height resolution adopted in the current study are similar to values in previous works using the visual obstruction method in the field (Barkman, 1988; Zehm et al., 2003; Limb et al., 2007; Sritarapipat et al., 2014) though comparisons to site-averaged heights were not conducted in those studies. The values in the current study are also similar to those of previous works indoors in which digital image analysis has been combined with the visual obstruction method (Hartmann et al., 2011; Tackenberg, 2007; Constantino et al., 2015).

The laser-scanning method can cover a greater spatial scale of several dozen to hundreds of m² with a millimeter to centimeter height resolution (Tilly et al., 2013; Tilly et al., 2014; Friedli et al., 2016). However, again, the laser scanning method has some obstacles to practical application (as mentioned in Section 5.1.1).

5.1.3 Cost and time required as well as the effects of different persons on analysis

The total cost of the developed system was about 300 USD. The employed camera (PlantCam, Wingscapes) cost approximately 100 USD, but is now discontinued by the manufacture. The current model is a TimelapseCam, which cost 110 USD in 2016. The rest of the materials including the level, the white wire net and the scale bar can be purchased for between 100 and 200 USD. The cost is expected to be roughly equal to that of the system used for the visual obstruction method; for example, Limb et al. (2007) mentioned that the cost of their system was 600 USD. Furthermore, the cost of the current system is much lower than that of a system using laser-scanning instruments. Even though heavy rain and strong winds were observed during the study period, the developed system worked continuously for the two rice growing seasons without any problems. Thus, the cost of running the system for multiple years should be low.

Overall, the time required to determine the plant heights for one rice growing season using the developed system is approximately 20 to 30 hours (see Section 4.1). This amount of time may be somewhat large for some researchers; however, the developed system does not require additional processing such as filtering algorithms to discern the plant canopy or the scale bar (Friedli et al., 2016; Sritarapipat et al., 2014), or fixing the reference surface to determine the absolute values of plant heights (Tilly et al., 2014). Thus, the total time required for data handling may be less than or similar to that using other measurement systems.

In the current study, two undergraduate students carried out the determination of plant heights for the same site over different years, and they achieved the same level of correspondence with the directly measured heights and required a similar amount of time for processing. Thus, the developed system produces consistent results that do not depend on the person who determines the plant height because this method does not require any special skills. In future, to further reduce the time required to carry out the method and obtain more uniform results that are not dependent on who processes the data, semi or full automatization of image analysis should be developed.

5.2 The displacement effect

Projecting any three-dimensional object onto a two-dimensional plane causes certain distortions. In the visual obstruction method, the displacement between the referenced scale bar and measured material (i.e. the horizontal distance between the camera and the scale bar differs from that between the camera and the material) affects height determination. Zehm (2003) pointed out this displacement effect and compensated for it by using the relationship between the estimated plant heights and directly measured ones. In the current study, a theoretical equation was derived to represent the displacement effect and its validity, including a certain amount of the lens distortion effect, confirmed by the indoor experiment described in Section 3.

Regarding the actual effect of displacement on measurements, during the early to middle period of the rice growing season, displacement error (\(h_{\text{a}} - h\), hereafter referred to as \(\delta h\)) should be small. In the early part of the rice growing season, the movable parts of rice (i.e. leaves and stems) are still short and thus have restricted movement. Hence, point of measurement will not differ greatly from the location of the scale bar. In the middle of the rice growing season (when the rice plant height is similar to that of the camera), the error should theoretically be close to zero.
because \( \delta h = 0 \) when \( h_i \) equals \( h_r \) (see equation [1]) even though rice plants grow rapidly during this time. In the later part of the rice growing season, the displacement error is expected to be large because the rice stems reach their maximum diameter of ca. 10 – 12 cm, which resulted in a longer displacement length.

The determined rice stem diameters showed ca. 1 to 12 cm, which was roughly 10% of the rice plant height. Therefore, taking \( \delta L \) as the half of the rice stem diameter, which is assumed to be 10% of the rice plant height, the dependence of \( \delta h \) on \( h_i \) can be calculated. The results for displacement error using an \( h_r \) range of 10 to 120 cm are shown in Fig. 7, and the seasonal variation in \( \delta h \) mentioned above was confirmed. That is, \( \delta h \) had low values of \( \approx 0.1 \) to \( \approx 0.2 \) cm, for an \( h_i \) range of ca. 10 to 50 cm, which means that the measured height values are underestimated (this corresponds to the early period of rice growth). Then, \( \delta h \) moves towards zero and becomes positive as \( h_i \) increases, where a positive \( \delta h \) indicates that the measured height values are overestimated. Finally, \( \delta h \) increased to a maximum of \( \approx 1.2 \) cm at an \( h_i \) of 120 cm. Because \( \delta h \) is a systematic error, though its absolute value is not large, it should be incorporated into data processing for precise plant height determination.

5.3 The border effect

When the visual obstruction method is employed, any plants between the camera and the target plants must be removed to prevent them from hindering image capture. In this study, the plant removal area was determined as \( L \times \) the row length used for averaging target plant heights (ca. 100 cm plus a margin), which yields ca. 3 m². This unplanted area may have caused a phenomenon known as the border effect, which is defined as a difference in the performance of the outermost row (i.e. the target plants) next to the unplanted area and the inner plants (Gomez and De Datta, 1971; Gomez, 1972). Generally, the outermost row of plants had significantly higher yields than the inner plants owing to advantageous environmental factors such as more solar energy, good ventilation and less competition for nutrients. This phenomenon has been reported in rice and other crops (Gomez and De Datta, 1971; Austin and Blackwell, 1980; Sato and Takahashi, 1983; Wang et al., 2013), and the amount of yield difference due to the border effect depends on the crop variety, planting density, and field size and shape (e.g. Kim and Yang, 1984; Wang et al., 2013).

With regard to plant heights, previous studies have revealed that the border effect is not very pronounced, even when yield increases are high. For example, Sato and Takahashi (1983) stated that in a rice field with a planting density of 11 plants per m², the plant heights in the outermost row were 97% to 99% of those in the inner row, though the relative percentages for aboveground biomass were 129% to 177%. A similar result was found by Ishihara et al. (1978). In the current study, the observed \( PH_{\text{ave}} \) and \( PH_{\text{ave}} \) fell close to or along the 1:1 line within ca. one standard deviation in the scatter plot in Fig. 6(B). This indicates that the border effect on plant height was negligible or its effect accounted for less than one standard deviation of \( PH_{\text{ave}} \). This small border effect may also be attributable to the relatively small unplanted area in this study (usually, the border effect is reported in fields with a length > 10 m). Consequently, the developed system succeeded in estimating representative plant heights for the study site despite the border effect.

6. Conclusions

A low-cost and low-labor system to determine plant heights in agricultural fields using the concept of the visual obstruction method was developed. The system can record continuous data and produce daily averages to a resolution of 1 cm in the vertical direction. Data were corrected for the displacement effect and then compared with directly measured and site-averaged plant heights. Good agreement was found between the current system and the two other data sets with a minor border effect on plant height at the site. Detailed seasonal and year-to-year variations in plant heights were also detected from the continuous data. Therefore, the developed system appears to fulfill all the requirements mentioned in Section 1.

The developed system can be applied to other crops that have similar maximum heights to rice (ca. 1.5 m) such as wheat, without any changes. Further, the system can likely be applied to crops that have higher maximum heights, such as maize, which often reaches 3 m, with modifications to the system by using two or more cameras to capture a larger area. After the camera and materials are set-up at the site, which took ca. 3 hours in this study, almost no effort is needed to maintain the system. This low maintenance makes the method highly suitable for remote sites that are hard to access frequently, particularly considering the time and labor savings over comparable measurement systems. Finally, in addition to the plant height measurement, the captured images contain useful information about the growing environments, including the presence of standing water, the water table depth, timing of panicle or ear emergence, and shape of the plant canopy as well as certain aspects of weather conditions. Therefore, the developed system can be adapted for a range of investigations such as ecosystem monitoring, near-surface remote sensing, plant phenotyping and other applications.

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References


