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Development of an Android-tablet-based system for analyzing light intensity distribution on a plant canopy surface

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ABSTRACT

An Android application system for the simple and real-time estimation of light intensity distribution on a plant canopy surface was developed, and its usefulness was tested under artificial lighting. The application system was designed to semi-automatically analyze the photosynthetic photon flux density (PPFD) distribution on the canopy from a reflection image acquired by the tablet. A single manual measurement by a quantum sensor at a point on the canopy was performed to build a regression model that estimated the PPFD on leaves from the pixel values of the image. Measured and estimated PPFD histograms, as well as parameters derived from histograms, were compared at three different growth stages of a plant canopy in a closed plant factory with artificial lighting. The measured and estimated histograms exhibited a similar pattern at each growth stage with close values of the parameters. The results suggested that the reflection-image-based estimation system developed in this study was a useful method for analyzing the light conditions under artificial lighting. Although the developed system will require additional improvements in automation and performance before it can be applied to actual cultivation-management procedures, this simple method for estimating the light intensity distribution is expected to help improve the efficiency and reproducibility of light control methods used for plant production.

1. Introduction

Recently, plant production systems, which are often referred to as plant factories where plants are grown under artificial lighting, have been studied for improving the production efficiency (Kozai, 2013) or for adding value to the products (Kato et al., 2011), and their practical use is spreading throughout Japan. Light intensity in a plant canopy critically affects the productivity in such plant factories; however, very little attention has been paid to the light intensity distribution on the canopy surface under artificial lighting conditions (Ibaraki and Shigemoto, 2013). Instead, the light intensity or, more specifically, the photosynthetic photon flux density (PPFD) is often evaluated only on or above the surface of cultivation beds (e.g., panels of hydroponics) that do not contain plants, and a single value of PPFD is listed as one of the lighting conditions in plant cultivation under artificial lighting (e.g., Sagardoy et al., 2009; Yoshida et al., 2012). However, the PPFD distribution on the leaves depends on both the canopy structure (i.e., distribution pattern of the leaf angle or orientation) and properties of the light source, including the luminous intensity distribution or the spatial arrangement (Ibaraki and Shigemoto, 2013). Therefore, a proper evaluation of the light intensity distribution on the canopy surface to improve the plant production efficiency and reproducibility under artificial lighting conditions is important.

Recent reports have suggested that diffuse reflection images of a plant canopy at a specific wavelength could be used to estimate the light intensity on the leaves (Ibaraki et al., 2012b). The use of images acquired from different directions minimizes the effect of specular reflection, and a high correlation between the PPFD and average pixel value (PV) in the reflection images could be observed. Based on this knowledge, a method to estimate the light intensity distribution from reflection images has been developed (Ibaraki et al., 2012b). A PPFD histogram of a tomato canopy under sunlight was constructed using this method (Ibaraki et al., 2012a). Moreover, the method enabled us to evaluate the efficiency of supplementary lighting based on the actual PPFD distribution on a tomato canopy surface irradiated with artificial light (Ibaraki and Shigemoto, 2013).

Mobile digital devices, such as smartphones and tablets, are now widespread and have begun to be used as practical information tools in agriculture. These multifunctional devices can be used to facilitate various farm management tasks (Lantzos et al., 2013), which had previously been performed by manual works or immobile computers. The devices are normally equipped with cameras

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and have the potential to be used as image-based tools to evaluate plant status (Kumar et al., 2012; Prasad et al., 2015) or environmental conditions (Moonrungsee et al., 2015). In addition, the software platforms embedded within these devices, e.g., Android, iOS, and others, provide tools for application system developers which allow us to create our own application systems for specialized purposes, such as agricultural use.

The objective of this study was to develop an Android application system for the simplified estimation of the light intensity distribution on a plant canopy surface. We also investigated the feasibility of an Android tablet application system under artificial light conditions and its application to light control methods to improve the efficiency and replication of plant production.

2. Materials and methods

2.1. Principle of PPFD distribution estimation on a canopy surface using reflection images

Leaf reflection images contain information related to the amount of light falling on the leaf (Ibaraki et al., 2012a). The light intensity distribution on a canopy surface was estimated in the current work with the reflection image-based method developed by Ibaraki et al. (2012b). In this method, the reflection images were acquired at a specific wavelength band, and the PPFD on leaves was estimated from the PV of the reflection images using a relation (regression model) between the PV and PPFD. The model was expressed by Eq. (1):

$$\mathrm{PPFD} = k \cdot \mathrm{PV}^{\frac{1}{\gamma}}, \tag{1}$$

where the proportional coefficient (k) was determined using a PPFD measured at one point on the canopy with a quantum sensor simultaneously with imaging and an average PV over the corresponding area in the image. For equation linearity, the PV was corrected by the gamma value (γ) of the imaging device (i.e., gamma correction).

The use of diffuse reflection (not specular reflection) in the estimation of the light intensity distribution is desirable because the specular reflection is highly dependent on the imaging direction, which results in estimation difficulty. In this method, the plant canopy reflection images were acquired from three slightly different directions. This was accomplished by moving the tablet in a horizontal direction at an interval of tens of degrees and averaging the PPFD distribution data derived from each image to reduce the influence of specular reflection on the light intensity estimation. One image was taken per one direction. The appropriate angle of the camera was determined to minimize specular reflection and not to intercept lighting by considering the lighting direction.

2.2. Plant materials and imaging device

Lettuce plants [*Lactuca sativa* L., ''Bio-salad'' (Sections 2.3 and 3.1) and ''Wearhead'' (Sections 2.5 and 3.2)] were hydroponically cultivated under white fluorescent lamps (FL40SS-w/37, Panasonic) in a plant factory at Yamaguchi University (Yamaguchi-shi, Japan) and were used as the plant materials.

Reflection images of the lettuce plant canopy were acquired with an Android tablet (Sony Tablet S SGPT112JP/S, Android OS 4.0.3) equipped with a CMOS camera (Sony, ''Exmor for mobile'' which has 5,110,000 valid pixels) through a blue–green bandpass filter (S76-BG7, Suruga) that was attached to the front of the camera. The filter had a peak wavelength of 480 nm and was chosen based on the results of a preliminary experiment that tested several optical filters (Ibaraki et al., 2012b).

To linearize the relation between the light intensity input and PV output (i.e., for gamma correction), the gamma value of the camera was predetermined. As gamma values may depend on exposure conditions, the gamma value of the camera was examined under various exposure conditions. Because the Application Programming Interface (API) used for developing the Android application (API level 15 platform for Android 4.0.3) did not provide functions to directly and separately control the camera exposure parameters (e.g., shutter speed, gain control, and ISO property), we used the automatic exposure (AE) and locking AE functions, which are provided in the Android API level 14 or higher. As AE was regarded as an integrated compensation of the exposure parameters, various exposure conditions could be constructed by activating AE under various light conditions. The images on a standard reflection board (Gray Cards, KODAK) were taken with the tablet's camera after changing the intensity of the irradiated light with multiple neutral density (ND) filters (S73-51-50, S73-51-40, S73-51-25, S73-51-13, Suruga). The relation between the light intensity (transmittance of ND filters) and PVs of the images on the board under several exposure conditions was then investigated. As a result, a gamma value of 0.7 was determined as the proper value to correct PVs for a wide range of exposure conditions based on the R^2 value that was close to 1, as shown in Fig. 1.

2.3. Comparison between measured and estimated PPFDs on the plant canopy surface

To confirm the possibility of performing the light intensity estimation with the Android tablet, the measured PPFDs were compared with estimated PPFDs at 30 different points on the canopy surface.

First, a reflection image of the lettuce canopy under white fluorescent lamps was acquired from the camera of the tablet. This image was analyzed manually according to the following analytical procedure. Subsequently, PPFDs at 30 points on the canopy surface were measured by a small quantum sensor (QSO-S, Apogee) that measures the photons as a voltage. The voltage values of the quantum sensor were converted to PPFD values. The PPFD was measured by setting the sensor just behind the target leaf at an angle similar to that of the leaf surface when the leaf was gently displaced by hand. The sensor was held at this position for approximately 5 s per one measurement. Additional images for marking the measurement points were acquired with a digital camera (SX110 IS, Canon).

For the 30 regions where the image corresponded with the measurement points, average PVs were calculated in approximate sizes of the quantum sensor (ϕ 18–20 pixels), and these PVs were then converted to PPFD by the linear model determined using the PPFD measured at one point on the canopy with the corresponding PV. The relation between the measured and estimated PPFDs was analyzed by calculating the root mean square error (*RMSE*, Eq. (2)) and the ratio of the *RMSE* to the averaged PPFD (Eq. (3)).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(X_i - x_i)^2}{n}}\ (\mu\mathrm{mol\ m^{-2}\ s^{-1}}), \tag{2}$$

where X_i is the measured PPFD at each measurement point, x_i is the estimated PPFD at each measurement point, and n is the number of measurement points.

$$E = \frac{RMSE}{\overline{X}} \times 100\ (\%), \tag{3}$$

where $\overline{X}$ is the average value of the measured PPFD, and E is the ratio of the *RMSE* to $\overline{X}$.