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ESTIMATION OF LEAF ANGLE DISTRIBUTION BASED ON STATISTICAL PROPERTIES OF LEAF SHADING DISTRIBUTION

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ABSTRACT

Leaf angle distribution is an important phenotype parameter that is related to photosynthesis. Thanks to the recent advent of drones and high-resolution imaging devices, leaf-scale aerial images with high spectral and spatial resolution are available. This work is the first attempt to utilize a single leaf-scale image to differentiate plants with different leaf angle distribution. First, assuming that a rice leaf surface resembles a section of a hemiellipsoid surface, a collection of rice leaf surfaces is approximated by a hemiellipsoid surface. Time-series of shading distributions on the hemiellipsoids with different structural parameters under different direct sunlight directions are generated. By investigating the statistical properties, i.e., skewness, kurtosis and the most probable intensity, of the frequencies of the simulated shading intensity that well-differentiate hemiellipsoids with different structural parameters, we identified an appropriate time slot, i.e., 11:00-12:30, for image acquisitions. Then, time-series leaf-scale images and depth maps of rice plants with/without silicate fertilizer under sunlight were collected. Based on the depth maps, it was confirmed that silicate fertilizer dosed leaves are more upright than leaves from non treated plants. It was demonstrated that 89% and 100% of kurtosis and the most probable intensity of the leaf-scale images during the appropriate time slot showed consistent relations with the simulations, which indicates that the proposed method is useful to distinguish different leaf angle distributions based on the frequency of shading intensity of rice leaf images.

Index Terms— Agriculture, leaf-scale optical image, leaf angle distribution, shading, phenotype

1. INTRODUCTION

With the recent emergence of affordable, high-performance drones and imagers, optical images with spatial and spectral high resolutions are available. Now, it is reasonable to expect that we can utilize the leaf-scale aerial images to extract leaf-scale traits of crops beyond area-, canopy-scale traits based on low-resolution conventional aerial images.

Leaf angles are important traits that are related to photosynthesis, in particular with the light-use efficiency and Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) [1]. Leaf-scale 3D reconstruction based on Structure from Motion (SfM) using multiview images [2] is possible in case of close-range measurements under controlled settings in which direct illumination and leaf movements can be neglected. However, when we try to apply the SfM technique to field aerial images that are captured by a drone from several viewpoints, leaf-scale 3D reconstruction is a challenge while estimations of more macroscopic traits, such as biomass and height, are possible. The main reasons for this limitation are three-fold, i.e., (1) shading effects and shadows caused by direct illumination make leaf-scale registration difficult, (2) in general, multiview aerial images are captured at different times inducing inconsistent/changeable postures of leaves due to wind, and (3) leaf-by-leaf registration is a challenge due to the difficulty in leaf segmentation. Another option for the 3D reconstruction is using depth sensors, e.g., LiDAR. However, the accuracy based on airborne depth sensors is not enough for leaf-scale analysis and in several cases, high quality devices are costly and could not be available.

Previously, we proposed a method that estimates leaf-angles based on time-series shading information on leaves [3]. We assume that the measured leaf radiance can be approximated by diffuse reflection as a multi-linear relation between surface normal, direct illumination and optical properties of leaves, in expectation that those elements can be estimated by using appropriate tensor decomposition technique. It was shown that leaf angle estimation is possible when multiple images under different sunlight directions are available. However, we need to assume that leaf angles are stable which is not a realistic setting. In addition, measured leaf radiance is a complex phenomenon including specular,

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diffuse, ambient reflection and transmission, which means that the measurements inevitably contain unknown nonlinear relations.

The objectives of this paper is to utilize a single leaf-scale image to differentiate plants with different leaf angle distribution that will be beneficial for plant breeding and precision agriculture. To the best of our knowledge, this paper is the first attempt to utilize a single leaf-scale image for leaf angle evaluation. The originality of the method is on using hemiellipsoid surface to approximate a collection of rice surface from a rice plant. In section 2, we propose a method that detects differences in leaf angle distribution by comparing statistical properties of measured shading distribution to simulated shading distribution. In section 3, the method is applied to leaf-scale rice images to compare shading distribution of rice paddies with/without silicate fertilizer.

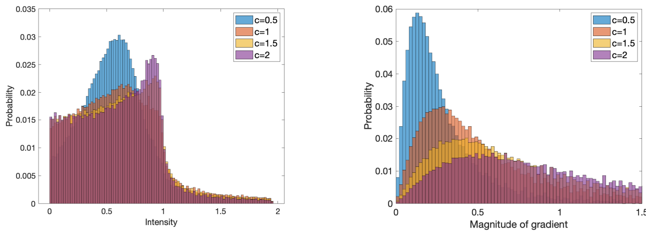
2. METHODS

Considering that a rice leaf surface resembles a half of a spherical lune, we assume that a collection of randomly distributed rice leaf surface can be rearranged to be approximated by a surface of hemiellipsoid that is defined by $x^2 + y^2 + z^2/c^2 = 1, (z > 0)$, where x and y are orthogonal coordinates in horizontal space while z is a perpendicular axis to the horizontal plane [4]. The degree of deformation along the z axis, that is related to the shape of the leaves, depends on the parameter c.

For the sake of simplicity, we assume that all leaves are under direct sunlight and the surface reflection is dichromatic that is defined as a sum of diffuse and specular reflection. Fig. 1 shows examples of histograms of shading intensities and gradients with different c values, where a higher c corresponds to more upright leaf angles whereas a leaf with a lower c is flatter.

The mapping from the intensity probability distribution to the surface angle probability distribution is not injective. However, we assume that the ill-posedness to estimate the surface angle probability distribution based on the intensity probability distribution is relaxed by restricting the surface model to hemiellipsoids. Our idea is that we can estimate leaf angle distribution by finding an optimal c value by which a simulated intensity probability distribution bestfits the intensity distribution of acquired shading distribution of leaves.

Let $p_h(I, c, \alpha)$ and $p_l(I, \alpha)$ be intensity probability distribution of a hemisphere and an acquired leaf images, where I, c and α are an intensity, a structure parameter and a sun elevation, respectively. The optimal structural parameter is given by $\hat{c}(\alpha) = \arg\min_{c} l(p_h(I, c, \alpha), p_l(I, \alpha))$, where $l(P, Q)$ is a metric that measures statistical difference between P and Q, e.g., Kullback-Leibler divergence. However, note that the probability distribution can be deformed by an unknown scaling factor because images are captured in auto-exposure and



(a) (b)

Fig. 1. ((a) the corresponding histograms of the intensities and (b) the corresponding histograms of the surface gradients.

auto-white-balance modes in some cases. Recall that skewness and kurtosis are higher order statistics (HOSs) that are scale invariant whereas it is not the case for lower order statistics, i.e., mean and variance.

Fig. 2(a),(b) shows transition of skewness and kurtosis of simulated shading distribution of hemiellipsoids with different c values under different direct sunlight directions corresponding to 9:23-16:33 on June 26, 2019 in Tsuruoka, Japan (see section 3.3 for more details). It is observed that more upright hemiellipsoids are constantly higher in skewness and kurtosis than less upright hemiellipsoid during a time slot with high sunelevations, i.e., 11:00-12:30.

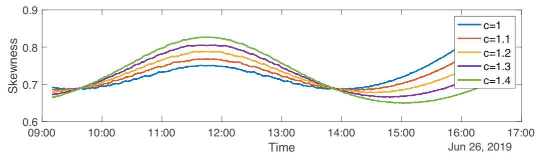
The drawback of the HOSs is that the distribution of the shading intensity is far different from normal distribution (i.e., averages of model skewness and kurtosis are approximately 0.6 and 4.0 respectively (see Fig. 2(a),(b))) whereas the baseline of the statistics is normal distribution. Therefore, there is a possibility that skewness and kurtosis are not appropriate to measure the difference in the probability distribution of shading intensities. In Fig. 1, we can observe that the most probable intensities depend on the c values. Fig. 2(c) shows transition of the most probable intensities of simulated shading distribution of hemiellipsoids with different c values under different direct sunlight directions corresponding to 9:23-16:33 on June 26, 2019 in Tsuruoka, Japan. It is observed that more upright hemiellipsoids are constantly lower in the most probable intensity than more upright hemiellipsoid during a time slot with high sunelevations, i.e., 10:00-13:30.

Overall, we identify 11:00-12:30 as an appropriate time slot for differentiating rice leaves with different leaf angle distributions. During the time slot, we estimate rice leaves with higher skewness and kurtosis to be more upright leaf angle distribution. Contrary, rice leaves with lower most probable intensity is regarded as more upright leaf angle distribution.

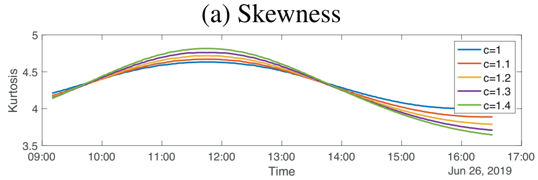
3. EXPERIMENTS

3.1. Data

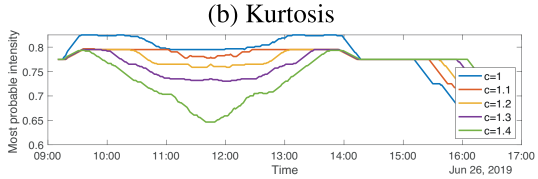
Two rice paddy fields were selected as the experimental fields at the Field Science Center, faculty of Agriculture, Yama-



(a) Skewness



(b) Kurtosis



(c) The most probable intensity

Fig. 2. Transition of skewness, kurtosis and the most probable intensities of shading intensities of hemiellipsoids.

gata University, Tsuruoka, Japan. After uniformly applying normal dose of fertilizer to all fields, silicate fertilizer (100 g SiO_2/m^2) was applied to a small plot (3 [m] $\times$ 3 [m]) for each field. It is known that the silicate fertilizer affects leaf angle distributions [5], so that it is expected that there would be significant differences in leaf angles between plots with silicate fertilizer and plots without silicate fertilizer.

Close-range rice images were collected at the paddy fields on June 26 and 27, 2019. The time of measurement and the weather conditions are shown in Table 1. The rice plants were approximately at the maximum tiller number stage that means the most visible portions were leaves and the stems are not apparent. For each field, two Intel RealSense D435 imagers were installed to compare the 3D structures and RGB color images of rice with/without silicate fertilizer. The dimensions of RGB and depth images are 640×480 (FOV: $69° \times 42°$) and 1280×720 (FOV: $74° \times 62°$) , respectively. Color and depth images were periodically measured at intervals of 1 minute. The color images were captured with auto-exposure and auto-white-balance modes.

Table 1. Color and depth image measurement of rice leaves

Variety	Fertilizer	June 26	June 27
Dewasansan (Field 1)	Control	9:23-10:15	8:20-10:23
	Silicate	9:10-16:31	8:21-10:22
Kamenoo (Field 2)	Control	10:24-16:32	-
	Silicate	10:05-16:33	-
Weather		mostly clear	cloudy

3.2. Leaf angle distribution based on depth images

In this section, we calculate leaf angle distributions based on the depth images and investigate the statistical difference between leaves with/without silicate fertilizer.

At first, depth images were converted to height images. Then, a leaf angle at each pixel was calculated from the depth images. Background and discontinuous regions were eliminated based on the depth and leaf angle values. Fig. 3 shows examples of empirical frequencies of the leaf angle distributions of rice without silicate fertilizer (control) and rice with silicate fertilizer. It is observed that fertilizer added rice plants have higher ratio of higher leaf angles than control rice plants. Fig. 4(a), (b) show daily variations of ratios of leaf angles of (a) 0.0-0.1 and (b) 0.9-1.0 of the Kamenoo field at 9:23 on June 26, 2019 (weather: mostly clear). The plots indicate that the previous observation (leaf angles dosed with silicate fertilizer distributed higher than leaf angles without silicate fertilizer) is consistent whole day. Fig.4(c), (d) show intra-day changes of ratios of leaf angles of 0.9-1.0 of the Dewasansan field on June 26 and 27, 2019 (weather: cloudy), in which silicate fertilizer dosed leaves are more upright than control leaves. A notable finding is that the depth maps measured by D435 produced reliable results under direct sunlight even if using the sensor outdoor, in particular under sunny condition, is not recommended by many people.

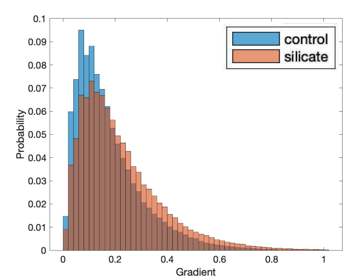
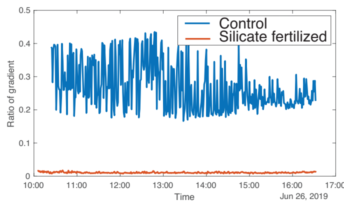


Fig. 3. Comparison of histograms of rice leaf angles without silicate fertilizer (control) and rice with silicate fertilizer.

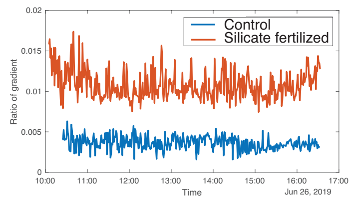
3.3. Shading distribution based on optical images

In this section, we investigate the relation between structural parameters c of hemiellipsoids and intra-day changes of HOSs and the most probable intensities.

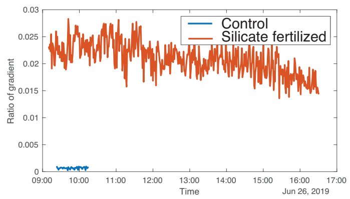
At first, sunlit leaf areas are extracted from color images based on a spectral angle between a representative color of green leaves and a given color was evaluated. The representative colors of green leaves were selected from diffuse reflection areas of leaves, and, then, areas of spectral angles less than 0.1 [rad] were selected. Among red, green and blue channels, the green layer was used to evaluate the statistical properties of shading on leaves because the green band



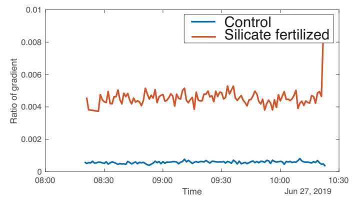
(a)



(b)

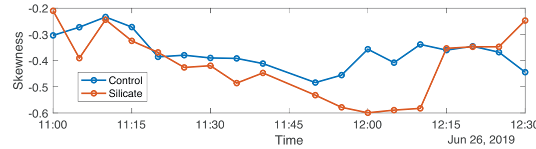


(c)

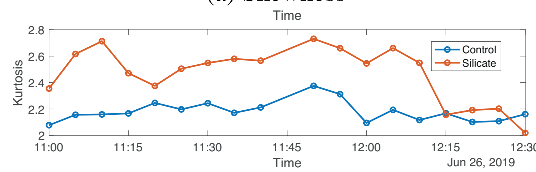


(d)

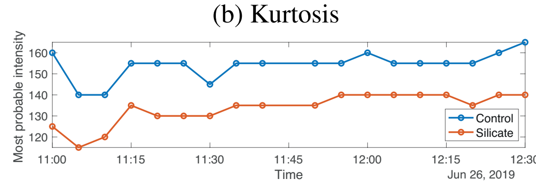
Fig. 4. Daily variation of ratios of leaf angles. (a) June 26, (Field 2), angle: 0.0-0.1, (b) June 26, (Field 2), angle: 0.9-1.0, (c) June 26, (Field 1), angle: 0.9-1.0, (d) June 27, (Field 1), angle: 0.9-1.0.



(a) Skewness



(b) Kurtosis



(c) The most probable intensity

Fig. 5. Transition of skewness, kurtosis and the most probable intensities of shading intensities of observations.

of leaves has the highest reflectance, so it is expected that signal-to-noise ratio is the highest in the band.

Fig. 5 shows the transition of skewness, kurtosis and the most probable intensity of shading distribution in field 1 during 11:00-12:30 on June 26, 2019. The magnitude relation in kurtosis and the most probable intensity between more upright rice leaves (silicate) and less upright rice leaves (control) are consistent with the results based on the hemiellipsoid surface model (section 2). In fact, 89% and 100% of kurtosis and the most probable intensity showed consistent relations with the simulations. Skewness showed inconsistent, i.e., 28%, relations which implies that some HOSs are not appropriate to compare statistical distributions that are far different from normal distribution.

4. CONCLUSIONS

In this paper, we proposed a method that utilize the shading distribution on sunlit rice leaves to differentiate rice plants with different leaf angle distributions. The experiments demonstrated that kurtosis and the most probable intensity are useful indices for the task. Although the hemisphere assumption is consistent with the results, it does not mean that a collection of linear leaf surface, e.g., the rice and wheat, is well-approximated by the simple hemiellipsoid model. Therefore, verification based on more realistic rice leaf surface model, e.g., [6], is the next thing to do. Needless to say, more careful investigation of leaf surface distribution is necessary when we deal with plant leaves with different layouts/shape/distributions, e.g., soybeans.

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