Research article

Monitoring of Crop Plant Height Based on DSM Data Obtained by Small Unmanned Vehicle Considering the Difference of Plant Shapes

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Abstract Unmanned Aerial Vehicle (UAV) has been recognized as a potential tool to obtain spatial information of crop state in small-scale farming fields. The objectives of this study are to assess the availability of UAV photographs to determine the plant height (PH) for three crop varieties (barley, oat, and perilla); and to evaluate the effect on the accuracy of the estimated PH caused by different plant shapes. The UAV photography and ground surveys were conducted weekly from May 31 to September 3, 2019, at the examination field of Obihiro University of Agriculture and Veterinary Medicine. The estimated PH was obtained from the differential value (D_value) of Digital Surface Models (DSMs) generated from UAV photographs through the Structure from Motion (SfM) process. The results demonstrate that the D_value of DSMs produced the highest estimation accuracy ($R^2 = 0.97$, $RMSE = 9$ cm) for perilla, which is a herb crop with luxuriant spade-shaped leaves, and a moderate estimation accuracy ($R^2 = 0.87$, $RMSE = 23$ cm) for oat, which is a grain crop making small spikes during the heading time with lanceolate leaves. The estimated PH produced the lowest accuracy ($R^2 = 0.34$, $RMSE = 28$ cm) for barley, which makes outward spikes with long prickly awns above the ear of grain. However, a higher accuracy ($R^2 = 0.67$, $RMSE = 17$ cm) for barley was obtained after a lodging of the spikes caused by rain on July 2. Furthermore, the accuracy of the estimated PH increased in both barley and perilla fields after corrected by plant coverage of the field. These findings suggest the D_value of DSMs obtained from UAV photographs can provide an accurate PH estimation for crops with luxuriant leaves like dicotyledons, but comparably less accurate estimation for crops with long and sharp leaves like monocots. Additionally, the elimination of the effect of unrecognizable factors such as long awns and non-plant factors such as the ground can also increase the accuracy of the estimated PH.

Keywords unmanned aerial vehicle, digital surface model, plant height estimation, plant shape

INTRODUCTION

Plant height (PH) is an important indicator for farmland management as it directly relates to crop growth status. However, traditional methods of PH measurement are time- and labor-consuming because of its requirement for mass sampling. In the past decade, the rapid development of Unmanned Aerial Vehicle (UAV) has provided an efficient, labor-saving, and precise approach to monitor crop biophysical parameters such as Normalized Difference Vegetation Index (NDVI) and Photochemical Reflectance Index (PRI) (Berni et al., 2009). Due to its ability of frequent aero photography, UAV has been also considered a suitable tool for crop PH monitoring. The method to detect crop PH using multi-temporal crop surface models (CSMs) generated with UAV-based imaging has been proved available by Bendig et al. (2013). This method has later been applied in several studies using different crops such as paddy rice (Tilly et al., 2014), summer barley (Bendig et al., 2014), and winter wheat (Lu et al., 2019).

However, no study has yet evaluated the estimated PH for crops with significant differences in plant shapes using UAV photographs taken under same flight conditions, and no study has discussed the effect on estimation accuracy of PH caused by different crop plant shapes. Thus, the objectives of this study are: (1) to determine the PH estimation accuracy for three subjects with different plant shapes; and (2) to evaluate the effect on PH estimation accuracy caused by plant shapes.

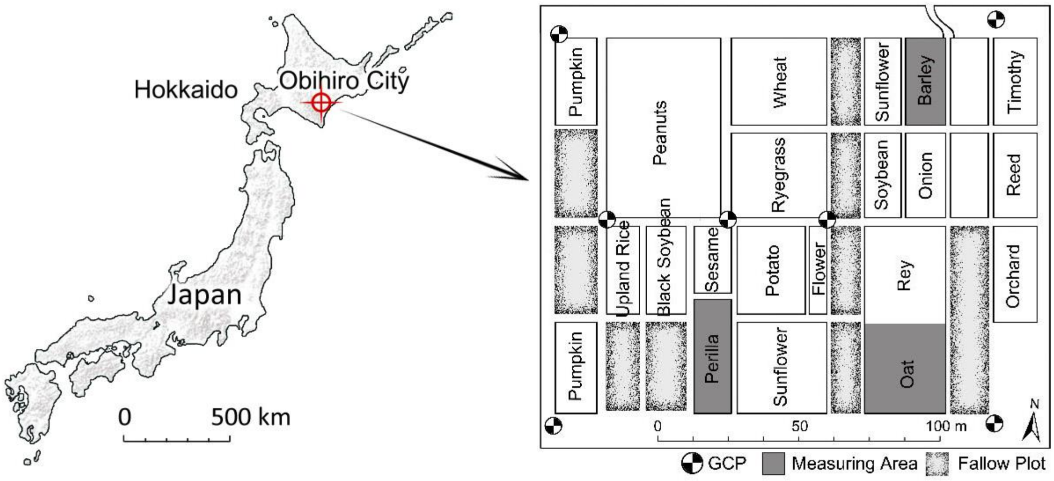

Fig. 1 Position and detail of the study site

METHODOLOGY

Surveys were carried out at the experimental field of Obihiro University of Agriculture and Veterinary Medicine in the city of Obihiro in Hokkaido, the largest and northmost prefecture of Japan (Fig. 1). The experimental field with a spatial extent of 180 m×160 m was divided into 22 small fields (average area: 700 m^2) and was cultivated with 19 different crop varieties. Barley field, oat field, and perilla field were used as the measuring areas to measure PH in this study. To provide accurate position information for the UAV photographs, ground control points (GCPs) were evenly settled at seven positions across the experimental field. Geographic coordinates of the GCPs were taken using a HiPer V RTK-GNSS receiver (TOPCON, Japan).

Photo. 1 Self-made PH measure

The UAV used in this study was a Phantom 4 Pro (DJI). The flights were carried out weekly from May 31 until September 3 (15 times) using an autopilot application known as Pix4D Capture (Pix4D). The UAV photographs were taken at 50 m above ground level on a flight path of double grid, with both forward and side overlap of 80%. The camera angle was adjusted to 70° from the horizon. Ground surveys to obtain the measured PH were conducted after each flight. Approximately 4-10 measuring points were settled and marked with pink marking tapes at each measuring area. A self-made PH measure was used to obtain the optimal value of PH under natural state (Photo. 1).

The UAV photographs were processed using a structure-from-motion (SfM) software, known as Agisoft Metashape 1.5.1 (Agisoft), to generate GCP-georeferenced DSMs (ground resolution: 5.6 cm) and orthomosaic photos (ground resolution: 1.6 cm). According to the method provided by Bendig et al. (2014), the differential value of DSMs (D_DSM) used for PH generation was calculated by subtracting the bare ground model from the DSM for each survey. The calculation of DSMs and extraction of PH value were conducted using ArcGIS Pro 2.3.1 (Esri). The measuring points marked with marking tapes were determined on the orthomosaic photos, and a circular polygon with a diameter of 20 cm was created at each measuring point. The maximum D_DSM value for each polygon was extracted and used as the estimated PH, which was compared to the measured PH. The coefficient of determination (R^2) and root mean square error (*RMSE*) were used to evaluate the PH estimation accuracy. In addition, within the UAV photographs of a field where the stems of crop were not fully extended, there was a considerable area of ground surface exposed through the leaves that may affect the value of the estimated PH. To find out the effect caused by the exposed ground area, the vegetation cover (VC) of barley field, where the VC increased significantly during the survey period, and perilla field, where the VC changed slightly, were calculated and used for the correction of estimated PH. A raster graphic editor software, Adobe Photoshop Creative Cloud 14.0 (Adobe Inc., USA), was used to extract and tally up the pixels of vegetation within a field plot to calculate the VC.

RESULTS

Figure 2 shows the comparisons of the time series between the measured and estimated PH for the three crop varieties. The measuring surveys were carried out weekly from June 19 until August 15 for barley, June 13 until September 3 for oat, and July 31 until September 3 for perilla. In the barley field, a lodging of spikes caused by rain happened on July 2 and continued until harvest. In the oat field, a soiling, which refers to the cutting of the leaves of crops for green feed in the middle of the growth stage, was carried out on July 24. In the perilla field, a thinning, which refers to the removal some plants of crop to make room for the others, was carried out on July 26. These natural or man-made phenomena were also reflected in the time-series of both estimated and measured PH.

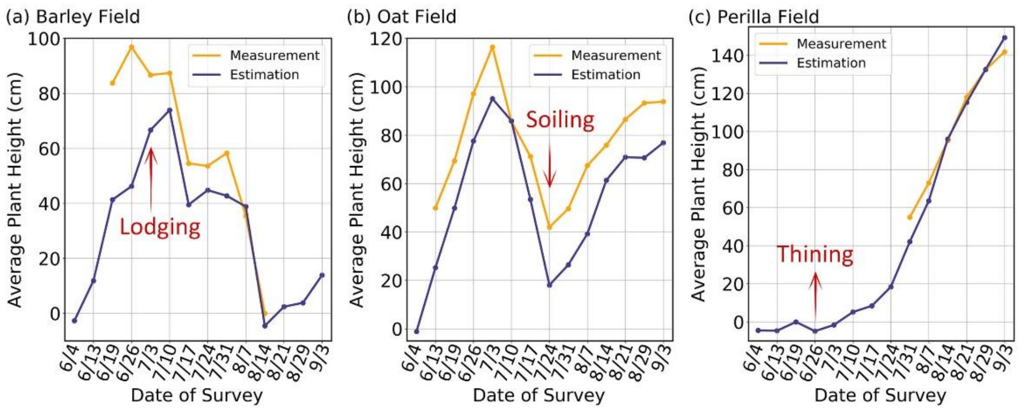

Fig. 2 Comparison of time series between measured and estimated PH

The relationship between the measured and estimated PH for each crop are shown in Fig. 3. A low correlation (R^2 = 0.43) and an *RMSE* of 27.9 cm were observed in the barley field. A high correlation (R^2 = 0.87) and an *RMSE* of 23.1cm were found in the oat field. An extremely high correlation (R^2 = 0.97) and a much lower *RMSE* of 9.2 cm were perceived in the perilla field. In view of the above, the estimated PH based on DSMs performed most satisfactorily for perilla, which is a dicotyledon crop. Between the other two varieties which are both monocotyledon crops, the estimated PH performed better for oat than for barley.

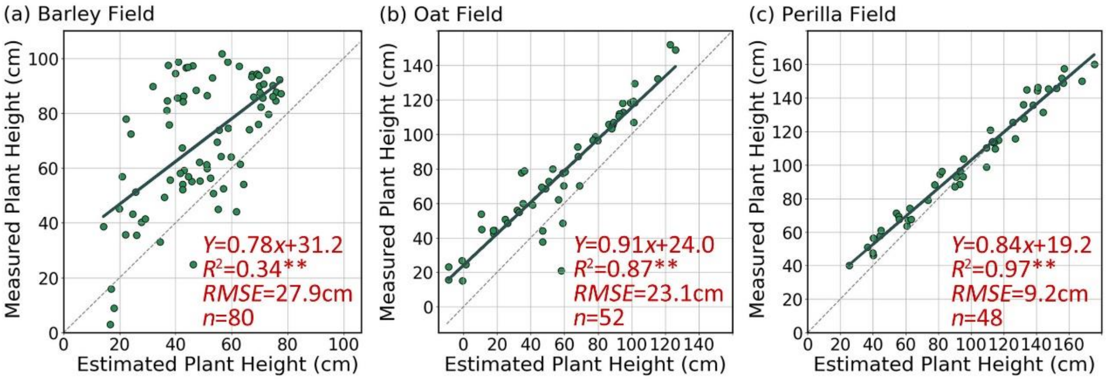

Fig. 3 Relationship between measured and estimated PH

The VC value and the dates of the UAV photographs by which the VC was calculated are shown in Table 1. In the barley field, the VC increased pronouncedly after the lodging from 88.9% (June 26) to 97.1% (July 3), while in the perilla field, the VC increased gradually from 90.4% (July 31) to 100.0% (September 3). The relationship between the measured PH and the estimated PH corrected by VC is shown in Fig. 4. In the barley field, the performance of the estimated PH after correction by VC (R^2 = 0.57, *RMSE* = 20.9 cm) was shown to be more accurate than before correction. In the perilla field, the estimation accuracy was slightly increased (R^2 = 0.97, *RMSE* = 7.9 cm) after it was corrected by VC.

Table 1 Vegetation Cover (VC) during survey period

(a) Barley Field

Date	June 19	June 26	July 3	July 10	July 17	July 24	July 31
VC	87.3%	88.9%	97.1%	98.8%	98.8%	99.2%	95.5%

(b) Perilla Field

Date	July 31	August 7	August 14	August 21	August 29	September 3
VC	87.3%	88.9%	97.1%	98.8%	98.8%	99.2%

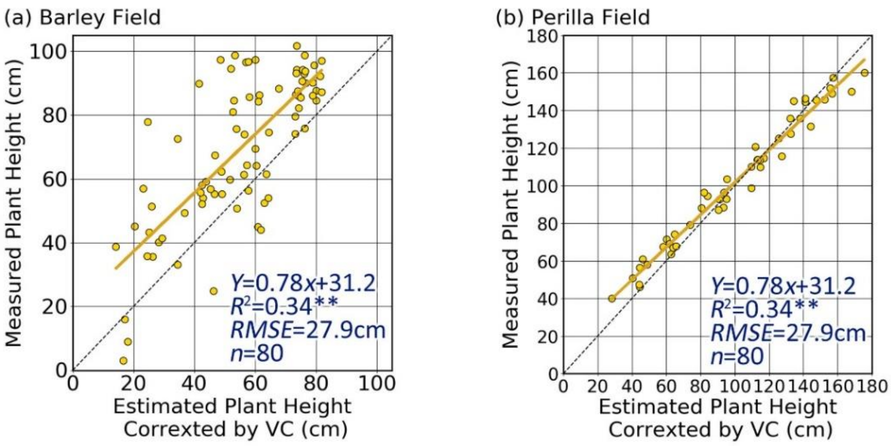

Fig. 4 Relationship between measured and estimated PH corrected by VC

DISCUSSION

The method to manually obtain the optimal measurement of PH under natural state has been a difficult issue due to the variety of PH in real farmland, and the individual difference between measurers (Bendig et al., 2014; Tilly et al., 2014). The problem of determining the representative mean of PH of a field plot was also discussed in an earlier study (Bendig et al., 2014). In addition, it is time- and labor-consuming even for skilled surveyors to set GCPs and obtain their precise coordinates every time before the UAV is flown over the field.

To solve these problems, a self-made PH measure was used in this study to obtain the measurement of PH properly and efficiently. A sliceable plastic plate with an area of 10 cm×20 cm was installed on a 150 cm-long pole, on which a tape measure was stuck (Pic. 1). When measuring the height, the plate was slid down slowly until there were most leaves reached it with the slightest shape changing. Each measurement was carried out at a certain measuring point, which was marked by a 100 cm-long pole (diameter: 0.5 cm) with a pink marking tape bound to it. These marking tapes could be found on the orthomosaic photos and used for the determination of the measuring points. Although there might still be a slight influence caused by a subjective judgement when adjusting the plate, it was expected to improve the accuracy of the measured PH through this method. Furthermore, in order to mitigate the cost of time and workforce caused by GCP settling and measuring, fixed points of GCPs were used in this study. Seven wooden posts (length: 20 cm), each with a nail at the top, were inserted into the ground at different positions in the experimental field. The geographic coordinates were taken once by RTK-GNSS on May 28 and were used for the generation of DSMs and orthomosaic photos ever since.

The comparison between the measured and estimated PH shows that the DSM-derived PH was generally lower than the measured value for barley and oat, which are both monocotyledons. In this study, each pixel of DSM represented the ground surface with an area of approximately 31.4cm^2 . Although the maximum value of D_DSM of the polygon area of a measuring point was extracted, it still represented the average height of several leaves including those in the lower position. Therefore, for crops which has detectable distance among leaves such as monocotyledons, the problem of underestimation should be considered when estimating the PH using DSM data.

Between the two monocotyledons used in this study, the estimated PH of oat performed better than barley. The reason for the low estimation accuracy of barley is considered to be the shape of the spikes. Barley produces peculiar, outward spikes with long, prickly awn (10 cm-15 cm) above the ear of grain. The height of the spikes was included in the measured PH. However, it is considered to be ignored during the DSM generation because it was too small to be recognized. To verify this possibility, the relationship between the measured and estimated PH before and after the lodging of spikes were calculated which are shown in Fig. 5. A low correlation (R^2 = 0.39, $RMSE$ = 47.1 cm) was observed before the lodging, while a medium correlation (R^2 = 0.67, $RMSE$ = 17.2 cm) was observed after the lodging. The lodging, which is the elimination of the effect of spikes, was helpful in increasing the PH estimation accuracy of the barley plant. Like barley, oat is also a poaceous crop. However, oat produces scattered spikes which have little effect on both measured and estimated PH. This is considered the reason why the DSM data showed a better performance in the PH estimation for the oat plant.

The extremely high accuracy of the estimated PH for the perilla plant is considered to be due to the luxuriant plant shape. Perilla is an erect, frontend crop that can grow to 0.6 m-2.0 m. The leaves are broad shaped with a length of approximately 10 cm-15 cm and grow densely on the stem. There was barely detectable distance among the canopy leaves in the perilla field during the survey period. This characteristic of the plant shape is considered as the reason why the estimated PH for perilla was much closer to the measured PH than the other two subjects, and even became higher than the measured PH at the late stage of the surveys. Although the underestimation problem of PH estimation using DSM has been suggested by many studies (Bendig et al., 2014; Lu et al., 2019), overestimation of the estimated PH caused by the growth of crop has not been observed and discussed yet. Considering this is probably a unique phenomenon of dicotyledon, future studies using other dicotyledon crops such as potatoes, peanuts, and soybean are expected to verify this assumption.

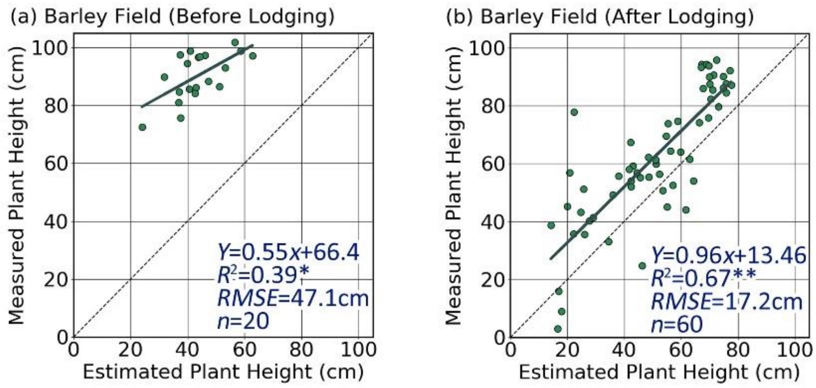

Fig. 5 Relationship between measured and estimated PH before and after lodging

Furthermore, correcting the estimated PH using VC was considered as a feasible method in this study to improve the estimation accuracy. The results showed in Fig. 5 indicate that the accuracy of the estimated PH for both barley and perilla plants increased after they were corrected with VC. VC is, thus, considered a potential indicator for PH estimation using UAV photographs.

CONCLUSION

In this study, the accuracy of estimating PH based on DSM data generated from UAV photographs for three crops with different plant shapes were compared. Although the estimation accuracy for barley was low during the whole survey period, it increased after the elimination of the effect of the spikes. For both barley and oat plants, the estimated PH were lower than the measured PH, because the DSM provided the average height of all factors within one pixel. However, the estimated PH for perilla was more accurate than the other subjects and surpassed the measured PH late in the growth stage due to its luxuriant plant shape. Future study is expected to discuss and verify this difference of estimation characteristic between monocotyledons and dicotyledons. Furthermore, VC was proved to be helpful to increase the estimation accuracy of PH for both barley and perilla plant.

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