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学位論文全文に代わる要約
Extended Summary in Lieu of Dissertation

氏名：
Name
Yu Liu

学位論文題目：
Title of Dissertation

Estimate SPAD values of naked barley leaves in the field by color-based vegetation index from UAV-derived RGB images
(ドローンのRGB画像から計算されたカラー指標に基づく裸麦の葉のSPAD値の推定)

学位論文要約：
Dissertation Summary

Barley, one of the oldest cultivated crops in the world, shares 7 percent of the global cereal production after maize, wheat and rice with 159.0 million tons all over the world at 2019 according to Food and Agriculture Organization of the United Nations. It is a major food source for the people in the cool and semi-arid areas of the world. In Japan, naked barley has been widely used to make mugimeshi, barley miso, and barley tea. It is important to apply adequate but suitable nitrogen fertilization during naked barley growth to get higher yield and avoid over-fertilizer. Therefore, it is necessary to apply nitrogen fertilization management at the right timing. Leaf chlorophyll content, which could be accurately assessed by Soil Plant Analysis Development (SPAD) value, could be used as a kind of fertilizer indicators because of the high correlation with nitrogen content in the crop leaves. Although the SPAD meter could provide a non-destructive way to measure the leaf SPAD value, the meter is time and labor sensitive on a large scale due to the limited measurement area and non-concurrency of the meter.

Unmanned Aerial Vehicle (UAV) can derive the canopy image of crops and has been currently attractive to researchers in precise agriculture for crop management and monitoring because of unlimited capture time and high spatial resolution in a large scale when compared to satellite remote sensing. The low-cost UAV systems mounted with a lightweight commercial digital color camera would be an alternative and cost-prohibitive method to make UAV popular among average farmers.

We investigated whether the regression models for SPAD values estimation of naked barley leaves which were constructed by the red, green, blue bands (RGB) values measured at the leaf level could be applied to estimate the SPAD values from the RGB values derived from the UAV images at the canopy level. First, linear regression models for estimating SPAD values were constructed using RGB values measured by a chroma meter with a stable internal light source at the leaf level. Second, the potential of using these models in the field was evaluated using RGB values estimated from images at the canopy level taken under sunlight by a UAV at different growth stages of the naked barley.

The SPAD values and RGB values used at the leaf level were called leaf-SPAD values and leaf-RGB values, respectively. The samples were selected randomly from the whole experimental area, and the total number of samples used in the leaf level was 25.

The SPAD values and RGB values used at the canopy level were called canopy-SPAD values and canopy-RGB values, respectively. The samples were obtained from 18 different experimental groups on 3 different dates (8^{th}, December, 2018; 8^{th}, January, 2019; and 5^{th}, February, 2019), and the total number of samples was 54.

The leaf-SPAD values and the corresponding leaf-RGB values at the leaf level were used to construct the linear regression models to estimate the SPAD values from RGB values. The regression models included three single variate linear regression models and four multivariate linear regression models. The equations of these regression models were shown in Table 1.

The SPAD values were estimated using seven linear regression models (shown as Table 1) from the leaf-RGB values at the leaf level. The coefficient of determination (R^2) between the measured leaf-SPAD values and estimated leaf-SPAD values from different linear regression models was displayed in Table 1. The R^2 showed that the single variate regression models, *SPAD(r)* and *SPAD(g)*, and the multivariate linear regression models, *SPAD(r, g), SPAD(r, b), SPAD(g, b),* and *SPAD(r, g, b),* could be used to estimate the SPAD values at the leaf value (R^2>=0.77). The linear regression model from the RGB values to the SPAD values could be regarded as an alternative method for estimating the SPAD values of naked barley leaves at the leaf level.

To analyze whether the leaf level SPAD value regression models could be applied to estimate the SPAD values at the canopy level, we calculated each group's SPAD values from the canopy-RGB values using the linear regression models constructed at the leaf level. The relationship between the measured canopy-SPAD values and the calculated SPAD values using different regression models were indicated by root mean square error (RMSE) and normalized root mean square error (NRMSE) in Table 1. According to the result, the calculated SPAD values from the *SPAD(g, b)* multivariate linear regression model had a low RMSE (5.05) and NRMSE (13.26 %) with canopy-SPAD values. This meant the *SPAD(g, b)* linear regression model constructed for the leaf level could be used to estimate the SPAD values of the naked barley leaves from the UAV RGB images at the canopy level in the field.

Therefore, the *SPAD(g, b)* regression model was regarded as the optimal model for estimating the SPAD of the naked barley leaves from RGB values at both the leaf and canopy levels.

Table 1. Relationship between measured SPAD values and estimated SPAD values from different linear regression models at the leaf level and the canopy level.

Linear Regression Model	Equation	Leaf Level (R^2)	Canopy Level (RMSE(NRMSE))
SPAD(r)	114.48 - 0.74 × *r*	0.77	8.55 (22.43%)
SPAD(g)	137.36 - 0.86 × *g*	0.86	7.35 (19.27%)
SPAD(b)	179.59 - 1.93 × *b*	0.44	22.14 (58.70%)
SPAD(r, g)	153.75 + 0.79 × *r* - 1.70 × *g*	0.90	12.01 (31.49%)
SPAD(r, b)	87.45 - 0.88 × *r* + 0.56 × *b*	0.78	8.88 (23.29%)
SPAD(g, b)	105.97 - 1.05 × *g* + 0.73 × *b*	0.89	5.05 (13.26%)
SPAD(r, g, b)	129.52 + 0.66 × *r* - 1.69 × *g* + 0.50 × *b*	0.91	8.49 (22.26%)

*Note: *SPAD(x)* is the SPAD value calculated from the variate of *x*, *r* is the value of R, *g* is the value of G, and *b* is the value of B.

Moreover, we investigated whether the RGB images captured by the UAV mounted with a commercial camera could be used in retrieving SPAD values of naked barley leaves under unstable photography conditions. We aimed to establish the optimal image processing methods for deriving good relationships between naked barley leaf SPAD values and vegetation indices (VIs) using different UAV images, and find a robust vegetation index for estimating the naked barley leaf SPAD values using UAV images taken at different photography conditions of solar and flight heights.

The UAV images were captured at 2 different flight heights (6.0 m for one experimental group in one image, and 50.0 m for eighteen experimental groups in one image) on 4 different dates (8^{th}, December, 2018; 8^{th}, January, 2019; 5^{th}, February, 2019; and 14^{th}, March, 2019). 48 image samples were used to detect the relationship between VIs and measured SPAD values by Pearson correlation. Linear regression models were fitted to each VI. 23 image samples were used to validate these regression models.

Maximum likelihood classification (MLC) was used to extract the vegetation cover by classifying UAV-derived RGB images at both flight heights. Moreover, the naked barley ear was additionally masked after vegetation extraction for the images of 6.0 m flight height because the ear was very evident in the image of the lower flight height but was not detailed captured by the image of higher flight height. According to the different image segmentation procedure, there were five kinds of UAV images: (1) original images at 6.0 m; (2) images by vegetation extraction but without naked barley ear mask processing at 6.0 m; (3) images by vegetation extraction with naked barley ear masked at 6.0 m; (4) original images at 50.0 m; and (5) images by vegetation extraction but without naked barley ear mask processing at 50.0 m. After image segmentation, 21 VIs were calculated for all kinds of the UAV images. The correlation between measured SPAD values and VIs was displayed by correlation coefficient (r) in Table 2.

In Table 2, the correlation coefficients after applying vegetation extraction were higher than that in the original imagery data for most VIs at both flight heights. Moreover, for the VIs calculated from UAV images at 6.0 m, the correlation coefficients showed even higher on the images after vegetation extraction and naked barley ears masked than that with the only vegetation extraction. In other words, the VIs had a better correlation with SPAD values of naked barley leaves after applying both vegetation extraction and naked barley ears masked.

According to Table 2, we could find that for the VIs derived from the image with the processing of vegetation extraction and naked barley ears mask at flight height of 6.0 m, the index of ‘R,’ ‘G,’ ‘B,’ ‘L*,’ ‘b*,’ ‘b*/a*,’ ‘G–B,’ ‘R–B,’ ‘2G–R–B,’ ‘(R+G+B)/3’ and ‘R/(R+G+B)’ showed significant correlation with SPAD values of naked barley leaves ($r > 0.70$). For the VIs derived from the image with the processing of vegetation extraction at the flight height of 50.0 m, the index of ‘L*,’ ‘b*,’ ‘B/G,’ ‘G–B,’ ‘2G–R–B,’ ‘B/(R+G+B),’ ‘(G–B)/(G+B)’ and ‘(2G–R–B)/(2G+R+B)’ showed significant correlation with SPAD values of naked barley leaves ($r > 0.70$). The high correlation between these VIs and SPAD values at different flight heights suggested that the color-based VIs calculated from UAV images have the ability to indicate SPAD values of naked barley leaves, even at different photography conditions.

Then, the result of the validation of these linear regression models for predicting SPAD values was shown in Table 3. The table suggested that the RMSE and NRMSE of the indices, which performed better correlations with SPAD values (Table 2), were lower than those which were not significantly correlated to SPAD values. Only the model of ‘G–B’ performed reasonably well at both flight heights .

Therefore, the index of ‘G–B’ could be regarded as the robust vegetation index to estimate SPAD values of naked barley leaves independent of the flight heights and photography conditions.

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Table 2. Correlation coefficients between SPAD values and vegetation indices derived from UAV images.

Vegetation indices	**UAV images acquired at 6.0m**			**UAV images acquired at 50.0m**	
	Original image	**Vegetation extraction (soil and shadow masked)**		**Original Image**	**Vegetation extraction (soil and shadow masked)**
		No naked barley ears masked	**Naked barley ears masked**		
R	-0.94**	-0.96**	-0.97**	-0.29	-0.41*
G	-0.93**	-0.95**	-0.95**	-0.61*	-0.70*
B	-0.80**	-0.79**	-0.80**	0.20	0.33
L*	-0.90**	-0.93**	-0.92**	-0.72**	-0.76**
a*	-0.28	-0.15	-0.12	0.56*	0.59*
b*	-0.51*	-0.67*	-0.71**	-0.87**	-0.90**
G/R	0.59*	0.58*	0.63*	-0.20	-0.20
B/G	0.02	0.22	0.26	0.77**	0.86**
B/R	0.35	0.47*	0.53*	0.52*	0.57*
b*/a*	0.19	0.80**	0.82**	-0.15	0.60*
G-B	-0.61*	-0.78**	-0.80**	-0.87**	-0.91**
R-B	0.62*	0.73**	0.77**	0.57*	0.61*
2G-R-B	-0.58*	-0.72**	-0.77**	-0.74**	-0.82**
(R+G+B)/3	-0.93**	-0.95**	-0.96**	-0.28	-0.40
R/(R+G+B)	-0.68*	-0.68*	-0.75**	-0.18	-0.20
G/(R+G+B)	0.21	0.12	0.12	-0.66*	-0.70*
B/(R+G+B)	0.16	0.32	0.37	0.71**	0.78**
(G-R)/(G+R)	0.57*	0.59*	0.63*	-0.22	-0.22
(R-B)/(R+B)	-0.35	-0.46*	-0.52*	-0.55*	-0.59*
(G-B)/(G+B)	-0.05	-0.21	-0.26	-0.77**	-0.84**
(2G-R-B)/(2G+R+B)	0.22	0.12	-0.04	-0.65*	-0.75**

** indicate the significance at p-value < 0.01; * indicate the significance at p-value < 0.05.

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Table 3. RMSE (NRMSE) of the validation for SPAD values estimation with vegetation indices derived from UAV images.

Vegetation indices	UAV images acquired at 6.0m			UAV images acquired at 50.0m	
	Original image	Vegetation extraction (soil and shadow masked)		Original Image	Vegetation extraction (soil and shadow masked)
		No naked barley ears masked	Naked barley ears masked		
R	2.61 (6.28 %)	2.40 (5.78 %)	2.03 (4.89 %)	8.55 (20.58 %)	8.81 (21.20 %)
G	3.24 (7.78 %)	3.18 (7.64 %)	2.88 (6.93 %)	8.29 (19.94 %)	7.87 (18.94 %)
B	5.24 (12.61 %)	5.44 (13.10 %)	5.50 (13.22 %)	8.38 (20.15 %)	8.84 (21.27 %)
L*	3.95 (9.49 %)	3.64 (8.76 %)	3.65 (8.79 %)	7.56 (18.18 %)	7.39 (17.77 %)
a*	8.20 (19.72 %)	8.20 (19.74 %)	8.28 (19.91 %)	7.06 (16.99 %)	7.20 (17.33 %)
b*	7.61 (18.30 %)	6.94 (16.68 %)	6.68 (16.06 %)	3.59 (8.63 %)	3.67 (8.82 %)
G/R	5.76 (13.86 %)	27.81 (66.91 %)	4.71 (11.32 %)	8.31 (19.99 %)	8.32 (20.02 %)
B/G	8.45 (20.33 %)	8.66 (20.84 %)	8.68 (20.89 %)	5.08 (12.23 %)	5.37 (12.93 %)
B/R	8.11 (19.51 %)	7.71 (18.54 %)	7.56 (18.18 %)	7.06 (16.98 %)	6.88 (16.55 %)
b*/a*	8.62 (20.73 %)	4.77 (11.47 %)	4.63 (11.14 %)	8.33 (20.05 %)	6.82 (16.40 %)
G-B	7.26 (17.46 %)	6.06 (14.59 %)	5.88 (14.14 %)	2.87 (6.91 %)	2.71 (6.51 %)
R-B	6.86 (16.50 %)	5.93 (14.27 %)	5.67 (13.65 %)	6.65 (15.99 %)	6.36 (15.31 %)
2G-R-B	7.47 (17.97 %)	6.49 (15.61 %)	6.09 (14.64 %)	5.16 (12.42 %)	4.32 (10.40 %)
(R+G+B)/3	3.05 (7.33 %)	2.85 (6.85 %)	2.89 (6.95 %)	8.57 (20.62 %)	9.02 (21.69 %)
R/(R+G+B)	5.04 (12.12 %)	4.72 (11.35 %)	4.32 (10.39 %)	8.25 (19.85 %)	8.20 (19.73 %)
G/(R+G+B)	7.98 (19.19 %)	8.06 (19.39 %)	8.06 (19.39 %)	6.74 (16.20 %)	6.92 (16.65 %)
B/(R+G+B)	8.50 (20.44 %)	8.50 (20.45 %)	8.47 (20.39 %)	5.75 (13.84 %)	5.59 (13.46 %)
(G-R)/(G+R)	6.11 (14.70 %)	5.01 (12.04 %)	4.76 (11.46%)	8.29 (19.94 %)	8.30 (19.98 %)
(R-B)/(R+B)	8.13 (19.56 %)	7.83 (18.85 %)	7.69 (18.49 %)	6.96 (16.74 %)	6.79 (16.33 %)
(G-B)/(G+B)	8.47 (20.39 %)	8.66 (20.83 %)	8.68 (20.88 %)	5.42 (13.05 %)	5.63 (13.55 %)
(2G-R-B)/(2G+R+B)	7.91 (19.03 %)	8.08 (19.45 %)	8.55 (20.57 %)	6.69 (16.10 %)	6.36 (15.31 %)

According to the tables above, we could find very high differences were occurred not only to the estimation accuracy between leaf level and canopy level but also to the relationship between the SPAD values and the VIs of ‘R’, ‘G’, and ‘B’ from images at different flight heights. the RGB values were obtained under the chroma meter’s stable internal light source for all leaf samples for the leaf level, but for the canopy level, the RGB values were obtained under sunlight on different days. The changes in solar intensity on different days leads to different UAV-image values, even for the same part. Our study in the field was an accuracy analysis based on the image-calculated values. Unstable image values would lead to estimation errors, which may be one reason for the difference between estimation accuracy of the leaf and canopy levels. In addition, the non-uniform brightness throughout whole RGB image at the flight height of 50.0 m which was not obvious in the images at 6.0 m may be another reason for the various estimation accuracy between different flight heights. The inconsistent brightness may due to the unstable flight and sunlight conditions and camera internal parameter adjustment in a large photography area of commercial digital camera mounted on the UAV in our study. But for the formula comprised of ‘G’ and ‘B’ in Table 1 and the VIs of ‘G-B’ in Table 2 and Table 3, they could be regarded as corrected values and may eliminate the brightness unbalance among different experimental groups our study.

Moreover, according to the vegetation reflectance spectrum in the visible bands, reflectivity was lowest in the B band and highest in the G band. The maximum difference among the visible bands was observed between the G and B bands, even for different leaf chlorophyll contents. Because of the maximum difference between the G and B bands, the signal noise may be ignored for the regression model comprising the G and B bands. For the other regression models, the signal noise could not be reduced like this because there was not much difference between the reflectivity of the other band as there was between the G and B bands. This finding may be one reason for the significant difference in estimation accuracy of the different regression models under different photography conditions.

In conclusion, our study investigated the potential of RGB images captured by UAV-mounted commercial digital camera for estimating the SPAD values of naked barley leaves. The multivariate linear regression model comprised of ‘G’ and ‘B’ could be regarded as the optimal model for SPAD value estimation of naked barley leaves at both leaf and canopy level, and showed it was alternative to estimate SPAD values of naked barley leaves from canopy RGB image in the field based on the regression models conducted at leaf level. Vegetation extraction and naked barley ear mask could

improve the correlation between image-calculated vegetation indices and SPAD values. The color-based vegetation index of ‘G-B’ showed significant relationship with SPAD values of naked barley leaves not only for combining different images at same flight height, but also for different flight heights separately. The result showed the great potentiality of the UAV-mounted with commercial digital color camera in retrieving SPAD values of naked barley leaves under inconsistent photography conditions. It is significant for farmers to take advantage of the cheap measurement system to monitor crops.

For a longer-term perspective, more deeply researches about the relationship between color-based vegetation indices and crop biophysical parameters (not only SPAD values but also above ground biomass, yield and so on) via UAV-mounted commercial digital camera and crop biophysical parameters should be expected