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主　論　文　の　要　旨

論文題目　Utilization of Multispectral-UAV system for Rice Crop Management
（マルチスペクトラルカメラ搭載 UAV を用いた水稲管理技術の開発）

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論 文 内 容 の 要 旨

Remote sensing using unmanned aerial vehicles (UAVs) and satellites is a rapidly growing technology in rice crop management today. While satellites are expected to cover a wide area at the national level and become an important platform for future agriculture, they have a low temporal and spatial resolution, making it difficult to develop technology for farmland. Therefore, there is a need to develop technology that can be applied to wide-area monitoring using UAVs, which can acquire crop data with higher temporal and spatial resolution, using satellites.

Crop parameters such as above-ground biomass (AGB) and leaf area index (LAI) of paddy rice are indicators of productivity and can be used to evaluate rice crop management for optimal grain yield and agricultural decision making. Previous studies have shown that this LAI and AGB of rice can be estimated using the vegetation index (VI) derived from spectral reflectance. Assuming that the development of a good LAI and AGB estimation model would be useful in predicting grain yield of paddy rice, this study improved the LAI and AGB estimation method using UAV-derived multispectral images and developed a grain yield estimation method using them.

In general, the accuracy of crop prediction models depends on the type of feature variables, model algorithms, and timing of data measurement, and these factors need to be considered in developing accurate crop prediction models. Therefore, the following four items were considered in this study.

(1) Evaluation of the impact of the use of texture variables on the accuracy of LAI-VI estimation models

(2) Evaluation of the impact of feature selection methods and the use of vegetation fraction (VF) on the rice AGB estimation model

3) Development of a grain yield prediction model using VI variables

4) Evaluation of optimal timing of data acquisition for grain yield prediction.

Experimental trials were conducted for two fertilizer trials and five rice cultivars during the 2020 and 2021 rice seasons. Multispectral images and the data of LAI, AGB, and grain yield were measured at four growth stage for each cultivar. UAV-derived variables such as VI and texture features calculated from the gray-level co-occurrence matrix (GLCM) were used as explanatory variables in the models.

Feature selection methods such as Recursive Feature Elimination (RFE), M-statistics, and z-tests were used in AGB estimation model while Exhaustive Feature Selection (EFS), variance threshold, and Variance Inflation Factor (VIF) were used in LAI estimation model to reduce the dimensions of the models by selecting parameters. For regression models, we evaluated the machine learning methods Support Vector Regression (SVR), Random Forest (RF), and Extreme Gradient Boost (XGBoost) for AGB estimation model while Multiple Linear Regression (MLR), SVR, RF, and Ridge Regression for LAI estimation model.

The results showed that RF gave stable results for LAI estimation of rice (R^2 = 0.60–0.62, RMSE = 0.68–0.73, m^2 / m^2), suggesting that feature selection had little effect on the performance of this model. Furthermore, combining specific reflectance data (RVI, GRVI) with texture data ($DTI_{(NIR,R)}$, $RTI_{(NIR,G)}$) improved the accuracy of LAI estimation for all five cultivars tested (R^2 = 0.68–0.82). This clearly shows that the use of texture and appropriate reflectance data can improve the accuracy of LAI estimation for rice.

We also considered the use of VF, a known alternative indicator of LAI, in the AGB estimation model. However, it is difficult to develop a model that stably distinguishes between plant and non-plant areas under outdoor conditions in this study, and no significant improvement in AGB estimation accuracy was observed even when VF was used as an additional explanatory variable.

We also developed a model to predict grain yield using time-specific VI measured at tillering, stem elongation, booting, and heading stages. Correlations between VI and grain yield showed that it was low among growth stages (r = 0.07–0.39). To improve the accuracy of grain yield prediction using VI as an explanatory variable, a multivariate regression model was selected. The results showed that RF performed the best among the regression models used in this study, including SVR, MLR, and Ridge regression, and the grain yield prediction using five VIs, including the normalized VI with Red Edge as an explanatory variable, was moderately weak (R^2 = 0.35 and RMSE = 0.78 ton/ha). The normalized VI with Red Edge contributes to grain yield prediction by providing optimal variability to the model. On the other hand, grain yield prediction was not substantially improved (R^2 = 0.39, RMSE = 0.75 ton/ha) when VI for the booting and heading stages were added as explanatory variables. When prediction models were created for each cultivar, better performance was observed for the cultivars Hatsushimo (R^2 = 0.50, RMSE = 0.84 ton/ha) and Nikomaru (R^2 = 0.50, RMSE = 0.53 ton/ha).

AGB and LAI estimations using multi-temporal VI were redeveloped in the XGBoost model and simulated throughout the growing season using Gompertz curves to determine the optimal timing of data acquisition for grain yield prediction for each cultivar. A single-day linear regression model was also constructed to examine prediction performance using simulated AGB and LAI values. The results showed that AGB and LAI could be estimated from VI (R^2 = 0.56–0.83, 0.57–0.73), and that the optimal timing of UAV flight varied from 4 to 31 days between the tillering and early heading periods for each cultivar. These findings are expected to help researchers save resources and time for numerous UAV flights to predict rice grain yield.

These results suggest that LAI and AGB estimates for two fertilizer trials and five varieties in a two-year experiment can be reasonably estimated using UAV-derived variables and machine learning models. Furthermore, direct prediction of grain yield using the cumulative VI provides comparable or better predictions than that of the estimated AGB and LAI using VI for some cultivars. Even variables with low correlation to crop parameters can be employed as explanatory variables indicating that a variety of inputs are essential for improved prediction.

In summary, our results showed that rice grain yield could be predicted before the heading stage using either VI or VI-estimated AGB and LAI, although it is cultivar-dependent. The analysis of the suitable timing of observations, which has not been evaluated in previous reports, allowed us to identify when yield estimation by satellite remote sensing can be used, and we believe this will contribute to the future widespread use of agricultural remote sensing.