

Doctoral Dissertation

**Application of Multiscale Remote Sensing and Simulation Modeling  
for Precision Forage Crop Management  
(Summary)**

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Forage crop is a key resource for ruminant meat and milk production. Precision information on forage growth and yields on the standing crop could help farmers make appropriate management decisions concerning, i.e., applying inputs according to the spatial variability and forage growth phenology, harvesting sequence of different fields according to yield and feed quality, purchasing the appropriate supplements, stocking rate, etc. More precise information on variations at field and regional level can give better knowledge on the links between yields and agricultural practices, soil and climate. Therefore, it has become extremely important to apply appropriate tools and technologies, including remote sensing (RS), global positioning system (GPS), geographical information systems (GIS) as well as growth simulation modeling, to support farmers to assess spatial variability within the forage cropping system and vary inputs rates to maximize profit.

To this end, this study focus on the technical developments, involving both tool applications placed at multi-platform and forage growth simulation modeling, to help optimize field-level management on the concept of being cost-effective, ease-of-use and delivering farmers forage crop information accurately and quickly.

With regard to applications of remote sensing tools, this thesis mainly explored image based remote sensing by developing two camera monitoring systems, including normal red-green-blue (RGB) and visible and near-infrared (V-NIR) camera systems.

Information on the spring growth status of winter forage crops is crucial for evaluating productivity and nutrient management. In chapter 2, the ground-based RGB camera system was firstly utilized to determine the spring quick growth stage (QGS) of Italian ryegrass. The camera system, installed in two Italian ryegrass fields at the farm of Hiroshima University, captured images automatically three times per day in red, green and blue channels over the growing season in 2012–13. Four presumed color intensities/indices were fitted using a logistic model to construct smoothed time-series data. Among the color intensities/indices, excess green was suggested to be the best parameter for monitoring seasonal changes. The root mean squared error of the estimated phenology dates against plant height was 7.7 days for the start-QGS and 2.8 days for the end-QGS. These results prove the applicability of the simple RGB camera system for forage phenology monitoring and demonstrates its advantages of low-cost and easy operation to users.

However, previous studies have suggested the potential use of NIR band of digital cameras for enhancing the accuracy of herbage growth estimation. To this context, in chapter 3, a simple visible and near-infrared (V-NIR) camera system was developed for monitoring the leaf area index (LAI) and quantifying the quick growth stage (QGS) of Italian ryegrass. RAW format images in the red, green and NIR channels over two growing seasons of 2014–15 and 2015–16 were captured hourly each day by the V-NIR camera system installed in three Italian ryegrass fields. Multiple linear regression (MLR) models that predict the forage LAI from the imagery data were calibrated and validated, with high coefficient of determination ( $R^2 = 0.79$ ) and low root-mean-square error (RMSEP = 1.09) between the measured and predicted LAIs. The predicted LAI to which three vegetation indices were compared was fitted against a logistic model to extract forage QGS from smoothed time-series data under various micro-meteorological and nutrient conditions. The result shows the time-series data of LAI can be applied for monitoring seasonal changes regardless of the environmental conditions. The RMSEP of the predicted phenology dates against the field-measured LAI was 0.58 and 5.2 days for the start- and end-QGS, respectively, under the high-yield condition in season 1. However, in season 2, only the start-QGS was

identifiable, with an RMSEP of 2.65 days under the nutritional stress condition. The forage LAI and QGS were predicted and identified more accurate and reliable, which suggests that the V-NIR camera system can be applied for monitoring seasonal changes in crop growth, aiding in better personalized crop and nutrient management.

Crop growth models are based on biophysical process, once developed for a crop, should be more universally applicable. The promising abilities of V-NIR camera system in monitoring crop LAI and QGS, make it possible to predict forage growth and yield by incorporating simulation modeling techniques. GRAMI, a crop growth model that can use remotely sensed information, was applied to the Italian ryegrass field. In chapter 4, a novel methodology for using GRAMI model along with the V-NIR camera monitoring system was demonstrated, to simulate herbage growth and assess its accuracy at plot canopy scale. Crop-specific model parameters were evaluated using field measurements at three experimental plots in the growing season of 2014-15. The model was validated using independent field data obtained at the same field in the season of 2015-16. Simulated values agreed well with the corresponding measurements, indicating the adaption of GRAMI to simulate herbage growth and the possibility to further develop the model by using a ground-based V-NIR camera system. The camera system provided daily observed leaf area index (LAI) as model inputs and for model recalibration, resulting in an agreement between the simulated and measured values, with high coefficient of determination ( $R^2 = 0.9$ ) and low root-mean-square error (RMSE = 69.9) for aboveground dry mass (AGDM) and  $R^2 = 0.69$ , RMSE = 1.52 for LAI. The results suggest that the V-NIR camera-based remote sensing, integrated with the GRAMI model, can be employed as an effective approach for simulating herbage growth and yields.

Unmanned aerial vehicle (UAV) system technology opens new horizons in precision agriculture for effective characterization of the variability in crop status at high spatial and temporal resolution. In order to increase the predict scale from several plots to an entire field, in chapter 5, the author present the use of an UAV equipped with a V-NIR camera in spatial field variability assessment and estimating herbage LAI and AGDM in an Italian ryegrass field. The multiple linear regression model was applied to establish relationships between measurements (ground truth) and V-NIR imagery obtained from UAV. The overall evaluation indicated that the estimated forage growth data were correlated well with the in-situ ground truth measurements.  $R^2$  and RMSE (n=21) for the correlation between forage LAI and infield control surveys is 0.88 and 0.82, respectively. The estimation accuracies of AGDM is examined with  $R^2$  and RMSE values (n=21) of 0.84 and 90.43 g m<sup>-2</sup>, respectively. Following these results, the UAV platform, equipped with a V-NIR camera, proves to be a suitable method to effectively characterize spatial field variation and assess forage growth.

In chapter 6, with the reproduced maps of forage growth parameters (LAI and BM), simulations of forage growth and yield with spatial variabilities were conducted. Forage growth and yield estimations over crop fields are essential procedures for effective forage crop management and economic return prediction, thereby benefiting the market growth of dairy industry. The advances in remote sensing have enhanced the process of monitoring the development of forage crops and estimating their yields. The author explored the potential of using GRAMI model, along with multiscale monitoring (UAV- and ground-based V-NIR imagery) to assess forage growth and yield in three Italian ryegrass fields during two growing seasons. Crop-specific model parameters were verified using field measured information from three experimental plots, while multiscale V-NIR imageries were used to estimate crop LAI for the within-season calibration of GRAM. Yield data for comparison with model estimates were acquired for each field from the farmers. The simulated yields were in statistical agreements with the corresponding measurements in field 1 and 2, with absolute errors lower than 4%

and 12% for two seasons, respectively. However, forage yield of field 3 was seriously underestimated (34.69%) due to the specular reflection effects, suggesting that further improvements on image processing and operations of UAV trails need to be made in the future. Overall, the methodology developed in this study to estimate forage growth and yield using GRAMI model and multiscale remote sensing, demonstrates reliable estimation abilities and appears to be applicable for predicting forage yields with a reasonable degree of accuracy.

Overall, the presented thesis can be seen as a first basis, highlighting the possibilities of integrating image-based multiscale remote sensing and simulation modeling technique to assist precision forage crop management at field scale. It is expected that the suggested approaches can lead to an improvement of the predictive accuracy in the context of biophysical parameter retrieval and be utilized in practice with cost-effective and really easy-to-use manners.