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

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学位論文題目：
Title of Dissertation

Developing irrigation management system in the dry season for rice cultivation by utilizing remote sensing data
(リモートセンシング・データを利用した乾季の水田における灌漑管理に関する研究)

学位論文要約：
Dissertation Summary

Local climate change cause uncertainty in water availability for agriculture. Changes in the local climate affect rainfall patterns and caused the shifting in the dry seasons, which forces farmers to shift the period of rice cultivation in the dry season. In most irrigated agricultural areas in Indonesia, rice is the main crop in the rainy season. Hence, rice production in the dry season generally decreases due to insufficient water availability, inappropriate planting schedule, and changes in cropping patterns. Various studies have discussed the onset and end of the dry season and even the rainy season for agricultural management. Thus, the dry season parameters (onset, end, and duration) are essential for irrigation management in rice cultivation.

Understanding how the dry season has changed in the past and how it will change in the future becomes an important issue for irrigation management and food security. In addition, monitoring rice production is an important aspect of maintaining regional food security to ensure the stability of the food supply, especially in the dry season. There are three rice planting seasons in Indonesia, namely, the wet season planting (1st planting season), followed first dry season planting (2nd planting season), and the second dry season planting (3rd planting season/crops season)

The utilization of remote sensing data can be one solution in monitoring rice cultivation and its production in a large-scale area during the dry season. On the other hand, remote sensing-based methods have been proven by several researchers as an effective alternative to estimating the rice field area and predicting its production. Therefore, the objectives of this study were: (1) to determine the dry season's onset, end and duration, and predicted ones for the near future; (2) to develop a monitoring system for rice production in the dry season by utilizing Landsat 8 Operational Land Imager (OLI), with the impact of the dry season parameters on rice production; and (3) to develop a monitoring system for the response of rice plant canopy to soil water and meteorological conditions using the aerial photograph. To achieve the first and second objectives, this research was conducted in Agam Regency, West Sumatra, Indonesia. Agam District is the largest irrigation area in West Sumatra Province, Indonesia with around 24,266 ha. The district covers 2,232.30 km² at altitudes 0 to 2891 m above sea level. Agam District is an agricultural zone with a total irrigated rice field area of 24,266 ha.

This study proposed a new approach to determine the dry season parameters by using annual cumulative rainfall for the past 35 years (1985 – 2019) in Agam District, West Sumatra, Indonesia. Daily rainfall measurements from 1985 to 2019 were obtained from 5 stations. Two rain gauge stations are located in Agam District (Canduang and Gumarang) and additional stations (Padang Panjang, Suliki, and Paraman Talang) are outside but close to this district. Missing rainfall data were predicted using the inverse distance weighting (IDW) method.

The 5th degree polynomial equation (quintic function) provides the highest correlation with cumulative rainfall data compared with other equations (5th polynomial: R^2 = 0.9961, 3rd polynomial: R^2 = 0.9942, logarithmic: R^2 = 0.7347, and exponential: R^2 = 0.9333). The example of quintic function fitted with cumulative rainfall at Candung station in 2019. In this study, the slope of cumulative rainfall for a year is presented as G_{rain}, which is the threshold for determining the dry season parameters. The minimum G_{rain} was set as 5.0 mm d^{-1} by assuming the minimum monthly rainfall for rainfed rice would be 150 mm $month^{-1}$. The first derivative of the cumulative rainfall function in describes the rate of change in cumulative rainfall, i.e., rainfall rate in the year. The onset of the dry season occurs when the rainfall rate decreases below the slope of cumulative rainfall ($F'(x) \leq G_{rain}$). The minimum rainfall rate in the dry season can be obtained by finding the roots of F'(x) or F"(x) = 0. Moreover, the rainfall rate (F'(x)) would increase gradually to the end of the dry season ($F'(x) \geq G_{rain}$), as shown in Fig. 2.

After determining the onset and end of the dry season in Agam District for the past 35 years, the yearly trends of the dry season parameters for each station were determined by using the nonparametric Mann-Kendall test and Sen's slope estimator. The dry season trends and predictions were analyzed individually to see the response at each station to local climate change, which could affect the rainfall pattern and distribution in the future. Further, the parameters for future dry seasons were predicted using the autoregressive integrated moving average (ARIMA) model for the next five years (2020 – 2025). The predicted DOY of the onset and end of the dry season is a product of several past observations and random errors, which is useful for forecasting future dry seasons. The applicability of the ARIMA model was evaluated using the Nash-Sutcliffe efficiency (NSE) which compares the average of the actual dry season parameters and the parameters predicted by ARIMA in Agam District from 2010 to 2019.

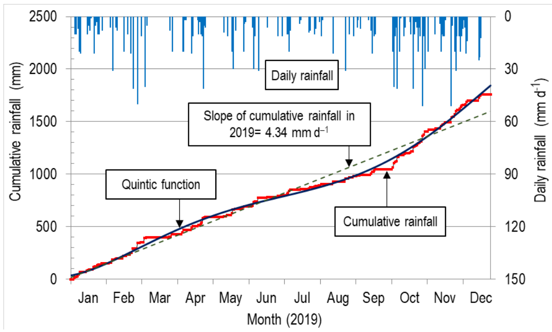

Fig. 1 A quintic function fitted to daily rainfall and cumulative rainfall at Candung station in 2019.

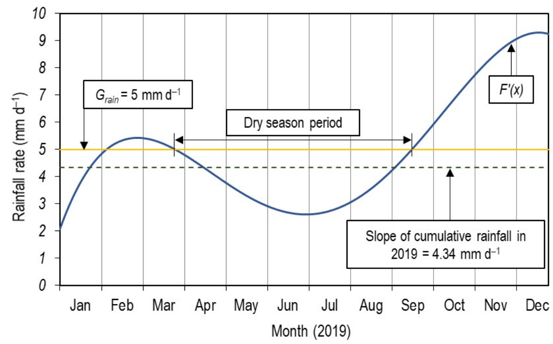

Fig. 2 The first derivative of cumulative rainfall (solid black line) *F′(x)* using Eq. (2-3) and the determined dry season period using *F′(x)* and G_{rain} at Candung station in 2019.

This study also examined the impact of the dry season on rice production using the Normalized Difference Vegetation Index (NDVI) of Landsat 8 Operational Land Imager (OLI) in Ampek Angkek sub-district, West Sumatra, Indonesia. Landsat-8 images were downloaded through USGS (United State Geological Survey) website with Landsat Collection 2 Level-1 (Lv1) and Level-2 (Lv2) products from 2017 to 2021 during the dry season.

Landsat 8 Lv1 was calibrated by the top of atmosphere (TOA) reflectance for targeted bands (i.e., bands 4 and 5). NDVI of Landsat-8 OLI level 1 with TOA reflectance and level 2 with surface reflectance was calculated on a composite image. A supervised classification method was applied to detect rice cultivation during the dry season from Landsat 8 OLI imageries. The reference of NDVI images was carried out by unmanned aerial vehicle (UAV) DJI Mavic Pro2, which is equipped with a multispectral camera (Yubaflex, http://www.bizworks.co.jp/YF/Spec.htm). The ground check was carried out to verify the NDVI values (from Landsat 8) that met each rice cultivation stage. NDVI analyses focused on the rice field in this sub-district downloaded from Geospatial Information Agency (BIG).

In this study, NDVI values (from UAV) were categorized into five rice field classifications, namely RF1 (for the rice field with land preparation and after transplanting), RF2 (rice cultivation between 40 days after transplanting (DAT) and 80 DAT), RF3 (rice cultivation after 80 DAT), RF4 (for the rice field with harvest and after harvest), and RF5 (crops cultivated in the rice fields). This study observed 217 ground checkpoints to classify the five rice field classifications in this sub-district. This study used the most popular yield estimation method, a regression model between NDVI images and the observed yield (field observation) focused on RF2 and RF3.

Field observation was conducted on 26 points of the rice fields that were cultivated during the dry season from September to October 2020. The measurement in the field observation consists of transplanting date and rice yield (ton ha^{-1}). In addition, the rice yield data from 2017 to 2021 was also collected from the Agricultural Department of Agam district. The dry season condition could affect rice production due to the amount of rainfall, the onset, and duration of the dry season. Pearson correlation analysis was performed to determine the relationship between dry season parameters (i.e., the amount of rainfall, the onset, the end, and the duration) and rice yield in this sub-district.

On the other hand, to achieve the third objective, this study was conducted in the rice field of Ehime University Senior High School, Matsuyama, Japan. Monitoring the response of rice plant canopy in terms of canopy temperature and NDVI to soil water and meteorological conditions using the aerial photograph. Thermal infrared (TIR) and NDVI imageries obtained by unmanned aerial vehicles (UAVs) may provide a means for determining canopies' temperature and plant conditions in the rice field. This study focused on the heading and flowering stage from July 31 (67 DAT) to August 10 (77 DAT), 2020. Even in one rice field, soil and water conditions were not the same in the whole field. This study's target points were in the middle and the edge of the rice fields to detect the difference in response between the two points.

The aerial photographs (i.e., NDVI and thermal) were taken every day during the heading (July 31-August 4) and the flowering stage (August 4-August 10) between 10:00 am and 11:30 am under clear sky conditions. The flight altitude was 20 m above ground level. DJI Go 4 and FreeFlight Thermal Applications were employed for UAV controlling and image acquiring. The targeted points in this study were in the middle and the edge of the rice field to detect the differences in response between the two points.

The result of this study showed that the 5th degree polynomial equation (quintic function) successfully correlated with the cumulative rainfall at the five stations (Candung, R^2= 0.9973; Gumarang, R^2= 0.9983; Padang Panjang, R^2= 0.9984; Suliki, R^2= 0.9966; and Paraman Talang, R^2= 0.9981). The dry season in Agam District started on April 28 (119 DOY) and ended on September 17 (261 DOY) with a duration of 142 days.

The averages of the onset and end of the dry season at the five stations showed positive trends, which were determined by using the Mann-Kendall test and Sen’s slope estimator, with probabilities of 78.83 and 84.42%, respectively. The duration of the dry season would become longer, with a probability of 67.54%. The ARIMA model for predicting the onset and end of the dry season showed good performance (Nash-Sutcliffe efficiency (NSE); NSE = 0.747) and very good performance (NSE = 0.769), respectively. The predicted dry season period in the next 5 years (2020 – 2025) would start between April 29 and May 5, and end between September 19 and October 4.

The impact of the dry season on rice production was successfully detected in Ampek Angkek sub-district using the NDVI from Landsat 8 Level 2. NDVI of Landsat 8 Lv2 had a good correlation with NDVI from the unmanned aerial vehicle (UAV) ($R^2 = 0.682$). The rice cultivation area in this sub-district in the dry season was successfully detected by NDVI from Landsat 8 OLI Lv2. This study successfully predicted rice production in the dry season by a linear function of NDVI from Landsat 8 Lv2 (y = 18.62970 x NDVI - 7.969) with a significant correlation ($R^2= 0.665$). By using the model found in this study, Ampek Angkek sub-district would produce 4038.9 tons of rice (yearly average) in the dry season from 1012.8 ha of the predicted rice field area.

This study successfully predicted rice production in the dry season by a linear function of NDVI of Landsat 8 Lv2 with a significant correlation ($R^2 = 0.665$). The total rainfall during the dry season showed a high correlation with rice production ($R^2 = 0.960$). In addition, the amount of rainfall in the dry season positively correlated with rice production, which is identified in Pearson's correlation of 0.981 (p-value = 0.003). Meanwhile, the onset, end, and duration have no significant correlation with predicted rice production, with Pearson's correlation of 0.219, -0.425, and -0.402, respectively. In addition, this study could explain that the amount of rainfall and the dry season parameters (i.e., the onset, the end, and the duration) had an impact on the predicted rice production in Ampek Angkek sub-district.

Irrigation water influences the canopy temperature and plant conditions in the rice field, which were clearly detected by the camera of UAVs. The NDVI camera value was lower than the actual ones (NDVI sensor), with a correlation coefficient of 0.63 (Fig. 3(a)). Meanwhile, thermal imagery by UAVs successfully detected the canopy temperature in the rice field, which hand-held TIR FLIR i5 was measured with a correlation coefficient of 0.83 (Fig. 3(b)). In addition, NDVI values from UAV camera correlated successfully with the Soil Plant Analysis Development (SPAD) chlorophyll meter at the same point ($R^2 = 0.96$), as shown in Fig. 4.

The irrigation water decreased the temperature of the soil surface, and it affected the observed canopy temperature. The soil surface temperature decreased during the irrigation process and reduced the rice canopy's temperature, as shown in Fig. 4-8. A thermal camera precisely represented the canopy temperature across the rice field. It detected that the edge of the rice field was higher than the middle ones, with an average differencing of 0.63 ºC. Before irrigation water started, soil surface temperature was more influenced by the air temperature. Irrigation water decreased the soil water temperature, and it would affect the canopy temperature. The canopy temperature would decrease when the vapor pressure deficit increases for both sides. Rice canopy structure with chlorophyll and water content decreased the air temperature and made the soil surface cooler. Moreover, in the middle of rice fields with high soil water content, it can maintain rising temperature and reduce soil water content for plants and their surrounding area.

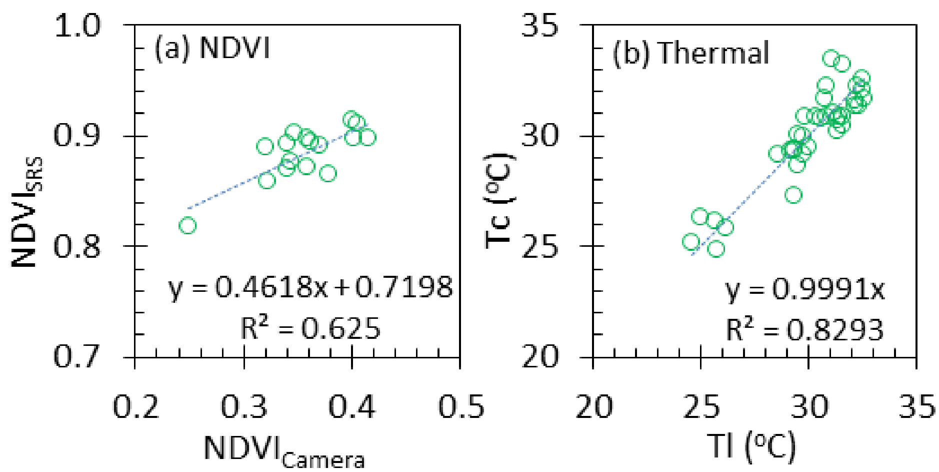

Fig. 3 Relationships between the camera and sensor measurement (a) NDVI and (b) canopy temperature.

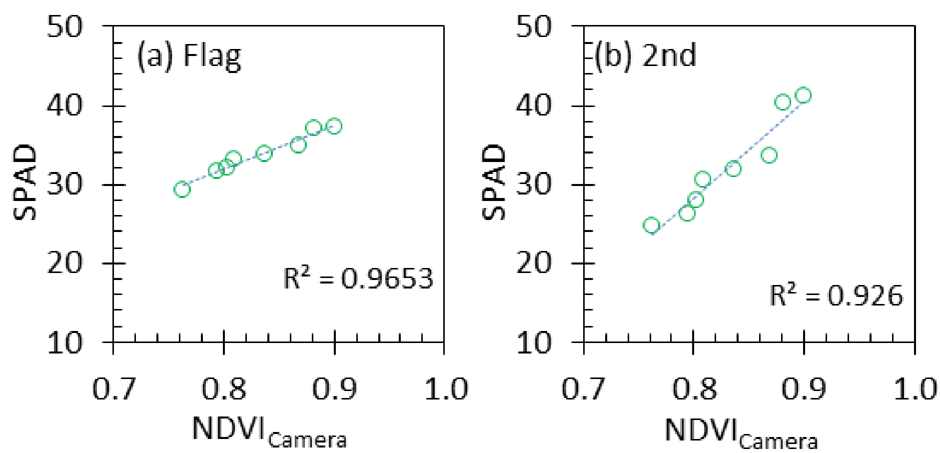

Fig. 4. Relationships between NDVI and SPAD value (a) Flag and (b) 2nd Leaves.

Furthermore, this study can be a valuable reference for the government, stakeholders, and decision-makers in formulating policies regarding preventing rice scarcity in the dry season. In Agam district, the onset and end of the dry season were predicted to be delayed around 4 and 9 days, respectively, for the next five years. The available water was mostly surplus in the rainy season (Jan-Mar and Oct-Dec) and dry season (Apr-Sep) with an average of 114 mm month-1 and 25 mm month-1, respectively. However, the available water decreased during the dry season and reached a deficit from May until July.

This study suggested that water users' association and relevant departments of local

government should prepare some countermeasures in irrigation management that can anticipate the water shortages problems during the dry season, as follows: (i) to reassess the distribution of agricultural water and the schedule for water use, (ii) to postpone the transplanting time to the first week of July in future dry seasons, (iii) to prepare additional irrigation water from a river, a small reservoir and artificial wells, (iv) to minimize water loss from the irrigation system, and (v) to strive for the application of water harvesting in the dry season. The new approach presented in this study would be applicable for predicting the dry season parameters for irrigation management in a region with dry and rainy seasons.