博 士 論 文 の 要 約

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学 位 論 文 題 名

Assessing oil palm growth condition in Indonesia using remote sensing techniques
（リモートセンシング技術を用いたインドネシアにおけるアブラヤシの
生育状態の評価）

The actual oil yield from oil palm is affected by agronomic practices, management practices, economic factors, and social and environmental factors. There were two main issues in the agronomic practices. First, the main disease of oil palms in Indonesia and Malaysia is basal stem rot disease (BSR), which is caused by *Ganoderma boninense*. There is no effective treatment for BSR, and all currently applied treatments only prolong the life of the oil palm. Second, fertilizer is an important factor affecting oil palm production, and accounts for 40–50% of the total costs of field upkeep. The fertilizer requirements of oil palm are determined based on analyses of leaf nutrient contents, like in other crops. Leaf samples are analyzed each year to optimize fertilizer inputs. This study had two main goals: to develop a fast and effective method to identify and monitor BSR disease, and to devise an inexpensive, rapid, and accurate method to monitor leaf nutrient status to optimize the fertilizer dosage. Remote sensing is a potential technique to achieve these goals and is already used in several agricultural practices.

1. A simple method for detection and counting of oil palm trees using high resolution multispectral satellite imagery

The detection method for BSR should be able to identify and map BSR infections quickly and inexpensively. Remote sensing is an appropriate strategy for such detection, and there is potential to improve the accuracy of remote sensing by combining it with machine-learning algorithms. For leaf nutrient monitoring, it would be advantageous to have an improved method that is simple, inexpensive, and accurate. Remote sensing techniques to estimate leaf nutrient status based on the reflectance of leaves have great potential in this regard. In the past, oil palm density has been determined by manually counting trees every year in oil palm plantations. The measurement of density provides important data related to palm productivity, fertilizer needed, weed control costs in a circle around each tree, laborers needed and needs for other activities. Manual counting requires many workers and has potential problems related to accuracy.

Remote sensing provides a potential approach for counting oil palm trees. The oil palm trees analyzed in this study have different ages and densities. QuickBird imagery was applied with the six pansharpening

methods and was compared with panchromatic QuickBird imagery. The black and white imagery from a false color composite of pansharpening imagery was processed in three ways: (1) oil palm tree detection, (2) delineation of the oil palm area using the red band, and (3) counting oil palm trees and accuracy assessment. For oil palm detection, we used several filters that contained a Sobel edge detector, texture analysis co-occurrence, and dilate, erode, high-pass, and opening filters. The results of this study improved upon the accuracy of several previous research studies that had an accuracy of about 90–95%.

The results of this study show (1) modified intensity-hue-saturation (IHS) Resolution Merge is suitable for 16-year-old oil palm trees and have rather high density with 100% accuracy; (2) Color Normalized (Brovey) is suitable for 21-year-old oil palm trees and have low density with 99.5% accuracy; (3) Subtractive Resolution Merge is suitable for 15- and 18-year-old oil palm trees and have a rather high density with 99.8% accuracy; (4) PC Spectral Sharpening with 99.3% accuracy is suitable for 10-year-old oil palm trees and have low density; and (5) for all study object conditions, Color Normalized (Brovey) and Wavelet Resolution Merge are two pansharpening methods that are suitable for oil palm tree extraction and counting with 98.9% and 98.4% accuracy, respectively. The 49,937 palms were identified by the Brovey method.

2. Random forest classification model of basal stem rot disease caused by *Ganoderma boninense* in oil palm plantations

We applied remote sensing and machine learning to identify and classify the two classes (healthy and unhealthy) of BSR infection with QuickBird imagery. The machine-learning models were support vector machine, random forest (RF), and classification and regression tree models used for predicting BSR disease in oil palm plantations. QuickBird imagery archived on 4 August 2008 was applied in three classifier models.

The RF model was best at predicting, classifying, and mapping oil palm BSR in terms of overall accuracy, producer accuracy, user accuracy, and kappa value. Using 75% of the data for training and 25% for testing, the RF classifier model achieved 91.43% overall accuracy. The RF classifier model used to produce outspread of the healthy and unhealthy oil palms using 49,937 data from the Brovey method and separated into 37,617 (75%) and 12,320 (25%) individuals, respectively.

3. Classifying multilevel infections of basal stem rot disease in oil palm plantation using WorldView-3 imagery and machine learning algorithms

WorldView-3 imagery has not been used to classify the four levels of BSR disease infection. The objectives were to predict the multi-levels of BSR disease infection using the eight multispectral bands of WorldView-3 imagery and supervised learning algorithms, and to describe the characteristics of the infection levels that can be identified by WorldView-3 imagery. Observation data were collected for 1923 oil palm trees with various levels of infection, including healthy trees, and unhealthy trees with three levels of symptoms from mild to severe. Decision tree, random forest, and support vector machine learning algorithms were applied. The overall accuracy was low and the accuracy was improved by around 1–5%

after outliers were removed from the data.

The results were affected by the criteria used to describe the BSR infection symptoms in the observation step. New criteria for BSR infection symptoms that can be identified using WorldView-3 imagery were described after selecting the data using threshold values that were determined based on the distribution of reflectance values of band 4. The new criteria of BSR infection symptoms based on this study were healthy oil palm trees (H) have no disease symptoms (asymptomatic); unhealthy oil initially symptomatic (UH1) have two unopened spears, emerging yellowish leaves, appearance of necrosis on older leave, and decreased leaflet size; unhealthy oil palm trees moderately symptomatic (UH2) have more than two unopened spears, yellowish leaves on middle to bottom part of canopy with the appearance of necrosis, 1–2 older leaves fractured; and unhealthy oil palm trees severely symptomatic (UH3) have more than three unopened spears, almost all older leave fractured, yellowish leaves along with wide range of necrosis, no new bunch/fruit, and damaged parts in the basal stems (rotten and hole). In future studies, we plan to use the new criteria of BSR infection symptoms to identify and classify BSR infection in oil palm plantations using an unmanned aerial vehicle with multispectral camera.

4. Predicting oil palm leaf nutrient contents in Kalimantan, Indonesia by measuring reflectance with a spectroradiometer

We studied leaf nutrient contents based on spectral reflectance data to explore suitable wavelengths for predicting the content of the most important leaf nutrients: nitrogen, phosphorus, potassium, calcium, magnesium, boron, copper, and zinc. The samples were taken from one plantation belonging to an oil palm company in Pundu, Central Kalimantan, Indonesia. The proposed vegetation indices, several common vegetation indices, and stepwise regression were used to build models for predicting leaf nutrient contents.

The ND and SR models using wavelength numbers X1423 and X1877 had strong positive correlations with N leaf nutrient analysis ($r = 0.731$), while X1164 and X1238 had strong positive correlations with Ca leaf nutrient analysis ($r = 0.707$). The P, K, Mg, B, Cu, and Zn had moderate positive correlations, with r values in the range of 0.575–0.699. Several vegetation indices commonly used for predicting leaf nutrient contents had lower r values than the proposed ND and SR in this study. For all leaf nutrient elements, models that involved all variables selected as significant through stepwise regression from the G1 (ultraviolet A) and G3 (green) to G6 (far red) wavelength groups had better performance than models that involved variables selected from each wavelength group individually. For predicting all leaf nutrient contents, variables from the G3 (green) wavelength group were always selected and these contributed more to building the models than any other groups. Our results indicate that our proposed vegetation indices and multivariate model can be used to predict leaf nutrient contents and determine the fertilizer requirements of oil palms. The next challenge will be to implement the proposed multivariate model using hyperspectral imagery because of the different spectral resolutions in spectroradiometer and hyperspectral image data. And another challenge in producing new techniques for precision agriculture, especially for predicting leaf nutrient contents in oil palm plantations, is adapting robust models and methods to the specific characteristics of the plantations.