論 文 の 内 容 の 要 旨

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論文題目 Geostatistical Method for Supporting Sustainable Forest Management in East and North Kalimantan, Indonesia

（インドネシア東および北カリマンタン州における持続的森林管理支援への
地球統計学手法の適用）

After 4 decades of continuous non-stop forest exploitation, East and North Kalimantan and many other forested regions in Indonesia are now suffering from various and complex problems such as deforestation, forest degradation, recurrent fires and forest encroachment in almost all of forested area (conservation, protection and production forest). Although sustainable forest management claimed to be the role model of Indonesian forest management system since the issuance of Principle Forestry Act in 1967, but the destruction and degradation of forest resources were so obvious and cannot be hidden. The advancement of remote sensing technology revealed the deforestation rate in Indonesia still at alarming rate. Recent publication in Science magazine (November 2013) by a research group from the University of Maryland had estimated Indonesian deforestation nearly two million ha from 2011-2012. Need more than commitment to handle these problems. Some serious actions and improvements on the policy need to be taken by the Government of Indonesia (i.e. Ministry of Forestry) in order to save forest from further devastation.

Started in 2002/2003, some of timber forest concessions in Indonesia had completed their first cutting period of 35 years. To extent the license for the second term, a forest inventory need to be undertaken as prerequisite. Old forest inventory method used line transect sampling method. In 2007, it was altered to systematic sampling method based on 0.25 ha plot covered all compartments inside the concession. Integration of plot data with GPS (global positioning system) is one of the significant improvements in term of data acquisition from forest inventory survey. The guideline for the new forest inventory was carefully prepared involving some experts in related field from reputable Indonesian universities. Now the guideline becomes an official standard operating procedure (SOP) for conducting forest inventory survey in timber forest concession level in Indonesia and became another significant improvement for Indonesian forestry policy..

Considering the role of East and North Kalimantan for Indonesian forestry sector as well as the fact that these provinces are still holding 83 active forest concessions and making up the largest

portion of East and North Kalimantan forest landscape (approximately 5.67 million ha), hence the need for better forest management becomes crucial. Study towards implementation on better forest management needs more and more attention and still relevant to these days to help such forest concessions to manage their natural forest in sustainable way.

In this study, geostatistics, a spatial statistics introduced by Matheron (1963) was examined to handle various spatial data collected from East and North Kalimantan forest. Some of these data are just recently became available such as ground survey data from new forest inventory as well as high spatial resolution remote sensing imagery. Geostatistics includes following sequential steps; (1) calculating gammavariance which is simply the mean squared difference of pair of observation or sample points; (2) constructing variogram (graph to exhibit the relationship between gammavariance and its corresponded distance); (3) fitting variogram with mathematical model (i.e. spherical, exponential, gaussian, etc); and (4) kriging spatial interpolation for estimating data at unknown location based on variogram mathematical model. For this study, geostatistics will be used to estimate (1) mean tree crown diameter, (2) stem volume and above ground biomass and (3) modeling site suitability of mangrove species in degraded forest land. This study was expected to give contribution to the implementation of better forest management in East and North Kalimantan and Indonesia in general, through optimizing available data to derive important information such as total stem volume or AGB estimation at timber forest concession level.

Study areas comprises four different sites. Three of them are located at natural timber forest concessions and one site is located at mangrove forest. From geographic point of view, those 4 sites represented various condition of tropical forest in East and North Kalimantan provinces. From lowland Dipterocarp forest with rough terrain (hilly area) in Malinau district, go down to more gentle slope terrain of lowland Dipterocarp forest in Berau district and end up at mangrove forest area in the east coast of Borneo Island. All sites also represented current situation of forest production area in East and North Kalimantan Provinces.

Floristic data from each site were collected through field measurement by establishing plots. Two hectares plots established in Malinau site where all tree above 20 cm dbh were measured and recorded. Two forest inventory dataset from 2 forest concessions in Berau site conducted in 2009 and 2010 were used. It was consist from hundreds of 0.25 ha plots. Trees above 10 cm dbh were measured. And approximately 1 ha plots in mangrove forest were established and all trees above 5 cm dbh were measured. To estimate mean tree crown diameter, two remote sensing images were used. A WorldView2 satellite image for Malinau site and ortho-rectified aerial photo for mangrove site. Multi spectral bands of WorldView2 image and aerial photo have fine spatial resolution 2 m and 0.15 m, respectively. And for site suitability mapping of mangrove species, soil and salinity samples in Mahakam Delta were also collected and analyzed in the laboratory.

This thesis was comprises 8 chapters and 4 main topics were discussed specifically to related objectives. First three chapters talked about the general information of current situation in tropical forest of East and North Kalimantan: problems, challenge and opportunities as well as general idea and

objectives of the study. The brief concept of geostatistical method by literature review was presented in chapter 2. And the general information of each site were given in chapter 3. General discussion and conclusion was presented in chapter 8.

In chapter 4, geostatistics was applied to estimate mean tree crown diameter from remote sensing image for two different site; lowland Dipterocarp and mangrove forest. The variogram analysis of WorldView2 (WV2) satellite image and aerial photo were succeed to estimate mean tree crown diameter of lowland Dipterocarp forest in Malinau and mangrove forest of Mahakam Delta, respectively. Green spectrum band of WorldView2 image gave the best prediction of mean crown diameter compared to blue, red and near infrared bands. The error of estimation of plot 1 and plot 2 is 2.98% and 2.30%, respectively. This error supposed not larger than 1 m. For mangrove forest, aerial photo was used to predict mean crown diameter with the lowest error about 6.19% or less than 0.5 m. Significant findings in this chapter were the important role of spectral signature of remote sensing image to the accuracy of estimation. In this study, green band looks promising but still need more exploration and further test. Second important finding was that variogram failed to estimate mean crown diameter of high density forest plantation sites. Close-spacing plantation suppressed tree crown growth and development which reflects in the image and produced smooth texture feature but less contrast.

The relationship between stem volume, basal area and above ground biomass (AGB) with remote sensing image pixels has been extensively studied for years even decades. In chapter 5, the relation of those 3 forest attributes with moderate spatial resolution satellite image was examined using a new forest inventory dataset of PT. Mardhika Insan Mulia (PT.MIM) forest concession in Berau district, East Kalimantan. As predictors, 37 spectral indices, 48 grey level co-occurrence matrix (GLCM)-based texture features and 6 variogram-based texture features were generated from 6 prominent bands of Landsat TM image. Landsat TM has 30 m of spatial resolution and cover large area in one single scene. Despite of cloud issue, Landsat images are still widely used in tropical countries such as Indonesia to produce land use or forest land cover classification.

Forest attributes derived from 266 plots location were later correlated to the corresponding pixel values from 91 modified and transformed Landsat TM image. Multi-linear regression model was used to analyzed the relationship and choose the best predictors. The output models were later used to estimate 3 forest attribute stocks in PT. MIM forest concession. In addition, estimation of forest stock based on one plot for one compartment (plot-to-compartment) was also applied together with estimation based on classic statistics (non-spatial approach where total forest stock is simply mean of forest attribute per ha multiply by the area of forest concession). In this chapter, MVI2 index and Contrast band 5 from GLCM texture were the best predictors. Multi-linear regression models estimated 3 forest attributes lesser than classic statistics but higher than one plot-to-compartment method. The latter method was official technique mentioned in the new forest inventory guideline which simply estimate compartment timber volume based on plots which location fell inside the compartment.

Different method for estimating total stem volume of timber forest concession was examined

in chapter 6. Using similar dataset obtained from new forest inventory design, total stem volume of PT. Karya Lestari forest concession was estimated using spatial interpolation technique. Two common spatial interpolation technique were tested i.e. inverse distance weighted (IDW) and kriging (geostatistical approach) to produce total stem volume of all trees above 10 cm dbh, 20 cm dbh, 50 cm dbh and 60 cm dbh. Additionally, total stem volume of commercial trees above 50 cm dbh and 60 cm dbh were also produced. Root mean squared error (RMSE) and mean of error were used to validate the accuracy of interpolation model. Kriging interpolation showed a slightly higher total stem volume estimation compared to IDW and plot-to-compartment-based estimation (an estimation method from new forest inventory guideline). However, kriging produced more natural (smoother) stem volume distribution map.

Using kriging interpolation, a set of soil and salinity data from point samples distributed in Mahakam delta were used to develop site suitability map of 14 mangrove species in chapter 7. Additional data such as ground height were derived from topographic map. Site suitability model was developed using site preference matrix for mangrove plantation project in Indonesia. Four environment factors (sand, clay, salinity and tidal inundation) were assumed control the mangrove species habitat. Different kriging parameters were tested in order to get reliable map of all factors. Geographic information system (GIS) was employed to perform variogram analysis, kriging interpolation, map construction as well as overlying of all maps of 4 factors to yield site suitability map. The output of site suitability map of mangrove species in Mahakam delta is expected to be the guidance for stakeholders in this region to rehabilitate more than 50% of degraded mangrove forest. Output maps will guide where and what species of mangrove need to be planted in certain local areas.

By applying geostatistical method, the objectives of this study were mostly accomplished. Geostatistical method is a reliable method that the author can offer to handle spatial data from tropical forest of East and North Kalimantan. For many years spatial data from timber forest concession were almost not available, but from the year 2007 new forest inventory system was introduced to timber forest concession and started to integrate plots and GPS. Likewise forest inventory data, the utilization of high spatial resolution remote sensing images were also still limited but just recently some companies started to afford it. This study was intended to enrich the option on how those spatial data should be handled in order to extract some important information which later can be used by forest managers or forest authority to support better performance in sustainable management of timber forest concession in Indonesia and particularly in East and North Kalimantan. Geostatistics is one of the promising method for handling spatial data from East and North Kalimantan forests and yet will fulfill the gap in this field of study because most of similar studies had been conducted in temperate forest or tropical forest of south America.