博士論文 （要約）

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）

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by

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A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy

In

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September, 2014

Acknowledgements

First of all, I would like to express my gratitude to Directorate General of Higher Education (DIKTI), the Indonesian Ministry of Education and Culture who has been awarded me with a scholarship to study at The University of Tokyo, one of the prominent universities in the world. Through this award, I have learned and experienced the excellent Japanese long standing academic tradition and also felt the fascinating Japanese culture and custom, their beautiful landscapes and sceneries as well as vibrant metropolis of Tokyo.

And foremost, my sincere and heartiest gratitude goes to Associate Professor Satoshi Tsuyuki, for his excellent supervision and guidance especially during construction of this thesis. Without him, this thesis would not be decent. Similarly, my gratitude also goes to Professor Makoto Inoue, head of Global Forest Environmental Studies (GFES) laboratory and also doctoral degree committee members: Professor Masaru Mizoguchi, Professor Seishi Ninomiya, Associate Professor Satoshi Tatsuhara and Associate Professor Fumiki Hosoi for their invaluable comments and advices during finalization of this thesis.

I also would like to express my gratitude to Prof. Dr. Mustofa Agung Sardjono from the Center of Social Forestry, University of Mulawarman and Dr. Muhammad Sumaryono, a senior lecturer of Faculty of Forestry, University of Mulawarman who has been supported and encouraged me to pursue my higher education in Japan. Not forget to mentioned Dr. Keiko Ioki, Dr. Abrar Juhar Muhammed, Dr. Chusnul Arif, Mr. Rustam, Mr. Wilson Wong Vun Chiong, Mr. Hari Kaskoyo, Mr. Teguh Purnama Sidiq for having a pleasant times through discussion, sharing knowledge, comments, advices, help and assistant. To all GFES lab members and fellow students which I could not mentioned personally one by one; thank you very much for your warm welcomed and assistantship in many things during three years of my study period.

My appreciation and thank also addresses to the management of PT. Total E&P Indonesia company, Ir. A.M. Guntur from PT. Batu Karang Sakti, Ir. Totok Suripto from PT. Karya Lestari, and the management of PT. Mardhika Insan Mulia for granted invaluable data and accessed to visit the forest and collect some data. Credit also goes to field crew during data collection: Mr. Asbona, Mr. Hisen, Mr. Hendri, Mr. Atma, Mr. Jaya and Mr. Fredy.

At last, my deepest gratefulness to my lovely wife Fitriyana, M.Si and my two beloved daughters: Aulia Septiana Putri and Sofya Oktafina Putri for their endless patience and support for the last three years. This achievement is utterly dedicated to all of you. And finally, I believe that all things happened is nothing but Allah will. All praised to Him for His mercy and His grace. May this humble works benefit to everyone.

Tokyo, September 2014

Ali Suhardiman

Abstract

After four 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, the destruction and degradation of forest resources were so obvious and cannot be hidden. The analysis of remote sensing data 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 extend the license for the second term, forest inventory needs to be undertaken as a prerequisite. Old forest inventory method used lines transect sampling method. In 2007, it was altered to systematic sampling method based on 0.25 ha of sample plot covering all compartments inside the concession. Integration of sample plot data with global positioning system (GPS) is one of the significant improvements in term of data acquisition during forest cruising. Now the guideline becomes an official standard operating procedure (SOP) for conducting forest inventory at timber forest concession level in Indonesia and became another significant improvement for Indonesian forestry policy.

Consider 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), 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 in 1963 was examined to handle various spatial data collected from East and North Kalimantan forest. Some of these data became just recently available such as ground sample plot data from the new forest inventory as well as high spatial resolution remote sensing imagery. Geostatistics includes the 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 (1) estimate mean tree crown diameter, (2) estimate forest attributes such as stem volume and aboveground biomass and (3) model 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 spatial data to derive important information such as total stem volume or aboveground biomass (AGB) estimation at timber forest concession level.

Study areas comprise 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 four sites represent various conditions of tropical forest in East and North Kalimantan provinces. Starting from lowland Dipterocarp forest with rough terrain (hilly area) in Malinau district, going down to gentler slope terrain of lowland Dipterocarp forest in Berau district and ending up at mangrove forest area in the east coast of Borneo Island. All sites also represent 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 trees above 20 cm dbh were measured and recorded. Two forest inventory dataset from two forest concessions in Berau site were used. Trees above 10 cm dbh were measured. The forest cruising to establish sample plots and tree measurement was conducted by field crew employed by forest concession. Once forest cruising finishes, it will comprise hundreds of sample plots data. In mangrove site, approximately one hectare of sample plot were established and all trees above 5 cm dbh were measured. To estimate mean tree crown diameter, two different remote sensing data 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 in Mahakam Delta, soil and salinity were collected at sample points. Soil samples were analyzed in the laboratory to determine the percentage of clay and sand fraction.

This thesis comprises eight chapters and four main topics were discussed specifically to related objectives. Chapter 1 discussed about the general information and current situation of tropical forest in East and North Kalimantan: the problems, challenges and opportunities, as well as the 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 study site was 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 using remote sensing image of two different sites; lowland Dipterocarp and mangrove forest. The variogram analysis of WorldView2 (WV2) satellite image and aerial photo were succeeded 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 lowest estimation error of mean tree crown diameter compared to the blue, red and near IR 1 bands. The lowest errors of estimation of plot 1 and plot 2 in lowland Dipterocarp forest were 2.98% and 2.30%, respectively. This error was not larger than one meter. For mangrove forest, aerial photo was used to predict mean tree crown diameter with the lowest error about 6.19% or less than 0.5 m. The significant findings in this chapter were the important role of spectral band of remote sensing data on the accuracy of estimation. Based on this study, green band looks promising but still need more exploration and further test especially for complex canopy structure such as lowland Dipterocarp forest. Second important finding was that variogram failed to estimate mean crown diameter of high density mangrove forest plantation sites. Close-spacing plantation suppressed tree crown growth and development. In the aerial photo, it produced smooth texture feature of tree crown with less edge of shadow. Consequently, tree crown became indistinguishable.

The relationship between forest attributes (basal area, stem volume and aboveground biomass) with remote sensing image pixels has been extensively studied for years even decades. In Chapter 5, the relation of three forest attributes with moderate spatial resolution of Landsat-5 TM image was examined using sample plots obtained from the 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 six variogram-based texture features were generated from six prominent bands of Landsat-5 TM image.

Astonishing result that Pearson correlation did not identified any significant correlation of three forest attributes derived from 266 sample plots with the corresponding pixel values of 91predictors (transformed image of Landsat-5 TM). To remove any potential outliers which supposed causing this problem, 2-dimensional Kalman filter was applied to 48 sample plots and finally succeed to correlate some of these predictors. I could not use all 266 sample plots simply because the limitation of 2-dimensional Kalman filter used in this study required data to be distributed regularly (equal number in X and Y direction). Multi-linear regression model was used to construct the relationship among the predictors that have significant correlation to forest attributes. The multi-linear regression model was used to estimate and map three forest attributes in PT. MIM forest concession. In addition, the estimation of total forest attributes based on "one plot for one compartment" (plot-to-compartment or P2C) method was compared with the estimation using multi-linear regression. In this chapter, MVI2 index and GLCM Contrast band 4 were the predictors that had greater contribution to the forest attributes estimation. Multi-linear regression models estimated three forest attributes higher than P2C method.

Different spatial interpolation techniques for estimating total stem volume of forest concession were examined and discussed in Chapter 6. Using similar forest inventory dataset obtained from forest cruising, total stem volume of PT. Karya Lestari forest concession was estimated. Three spatial interpolation techniques were tested i.e. inverse distance weighted (IDW), natural neighbor, and kriging (geostatistical approach), to estimate total stem volume of all trees above 10 cm dbh, above 20 cm dbh, above 50 cm dbh and above 60 cm dbh. Additionally, total stem volume of commercial trees above 50 cm dbh and 60 cm dbh were also estimated. Root mean square error (RMSE) and mean of prediction error (ME) were used to evaluate and select the suitable spatial interpolation technique. Kriging interpolation was selected as the suitable technique because it showed the smallest difference of RMSE and ME value compared to natural neighbor and IDW technique. Furthermore, in this study, kriging interpolation showed slightly higher stem volume estimation compared to P2C method.

Using kriging interpolation, a set of soil and salinity data from sample points distributed in Mahakam delta were used to develop site suitability maps of 14 mangrove species (Chapter 7). Additional data such as ground height (elevation) points on the study area were collected from topographic map. Site suitability model was developed using site species preference information issued by Indonesian Ministry of Forestry which was prepared as field guidance of mangrove rehabilitation project in Indonesia. Four environmental factors (sand, clay, salinity and tidal inundation) were assumed control the mangrove species habitat. Geographic information system (GIS) was employed to perform variogram analysis, kriging interpolation, and classification of four environmental factor data. The final step was overlaying classified environmental factor maps to yield site suitability maps. The output maps are expected to be the field guidance for stakeholders in Mahakam delta region to rehabilitate mangrove forest degraded more than 50% of area. Output maps will guide where and what species of mangrove is needed to be planted in certain local areas.

By applying geostatistical method, the objectives of this study were mostly accomplished except for variogram texture features as predictor of forest attribute which showed poor performance compared to spectral indices and GLCM texture features. Geostatistical method is a promising method that author can offer to handle spatial data from tropical forest of East and North Kalimantan. For many years spatial data of forest concessions were almost not available and the sample plot data analysis was relying on classical statistics. But since 2007, the outcomes of the newly introduced forest inventory system from forest concessions are definitely spatial data. Suddenly, it brought many opportunities to use various methods and techniques to derive such essential information to support forest management. Likewise forest inventory data, the utilization of high spatial resolution of remote sensing imagery for forest concession is just initiated and it also brings the opportunity to conduct various studies where the results may be used to support forest management. Using geostatistical method, this study will enrich the knowledge on how spatial data of tropical forest can be used optimally by forest managers or forest authorities to support sustainable forest management of forest concession in Indonesia, particularly in East and North Kalimantan.

Table of Contents

List of Figures

Chapter I.

Introduction

1.1. Background

Indonesia is the largest archipelagic country in the tropical region. The country's territory stretches for more than 5,000 km from east to west and 1,700 km north to south consisting of more than 17,000 islands. Indonesia is home for the third largest tropical forest in the world after Brazil and Democratic Republic of Congo (Jong, 1997). But in term of endemic vascular plants species, Indonesia is the second richest country in the world after Brazil (Conservation International, 2000 cited by Williams et al., 2001). The number of vascular plants (*Angiosperms*, *Gymnosperms* and *Pterydophytes*) in Kalimantan or Borneo Island itself is estimated to be 5,524 species, making it the second diverse region next to Sumatra Island which hosts approximately 8,538 species (Indonesian Ministry of Environment, 2009).

Furthermore, Indonesian tropical forest is not only rich in biodiversity, but also diverse in term of forest types. In Borneo, forests range from mangrove forest at the shoreline to mountainous region in the deep heart of the island. Mangrove forest mostly occupies muddy coastal area or river estuary while most of the Borneo lowland is inhabited by species from family of *Fagaceae*, *Myrtaceae*, *Lauraceae* and *Dipterocarpaceae*. Other common forest type includes peat forest area which is located in most south and west part of Indonesian Borneo and heath forest or *kerangas*.

By the government of Indonesia, these forests are divided into three main categories based on the expected roles and function in the future management and utilization. First category is the conservation forest. It is the most conservative forest management in Indonesia which intended only for conserving and preserving biodiversity (plants and animals) and their habitat. Timber production is prohibited and human interference is limited except for a few things such as research and monitoring. The second category is protection forest. In this area, forest is allotted and appointed to restrain hydrologic function and water catchment for supporting any activities (especially human activities) in the downstream areas such as fresh water sources and flood control. The third category is production forest where log and timber are intentionally produced for economic purposes. Altogether they make up nearly 131.3 million hectares of Indonesian forest stretched from Aceh province at the most western side to the Papua province in the most eastern part (Indonesian Ministry of Forestry, 2011).

In term of timber production, tropical forest especially in Borneo or Kalimantan is home of numerous valuable trees such as Dipterocarp species. Although, tropical climate produce a poor soil (a thin layer of fertile soil due to intense bleaching from rain and faster decomposition of leaves litter), surprisingly trees, especially from Dipterocarp species, grow enormously to some extent reaching 1.5 meter in diameter at breast height (dbh). Recent study even revealed that Bornean forest has higher rates of aboveground biomass production compared to Amazonian tropical forest in Brazil (Banin et al., 2014) due to the abundance of Dipterocarp trees (Slik et al., 2010).

As most of commercial trees in Borneo Island are among member of group of Dipterocarp species, it is not surprising if Kalimantan became a major contributor of timber production in Indonesia. Low population density coupled by flat slope of the region and innumerable stream and river networks that made timber and logistics transportation easy, have made Kalimantan forest as timber heaven especially during the golden period of timber exploitation in 1970's (Obidzinski, 2003).

Because of these benefits i.e. timber and non timber products, forest has been utilized for centuries by indigenous and local communities in Borneo. However local communities often value forests in a rather different way than professional foresters or governments do. While modern forest management system is focused mainly on the timber production, local communities see forest as an integral part of their livelihood. For them forest is not only timber sources for building houses or income generation but also for food sources, medicinal plants, agricultural lands and a social and cultural identity including conservation of their religious beliefs (Wiersum, 1997).

Despite of their important role and uniqueness, tropical forests in the world and particularly in Borneo are currently facing common threat that is deforestation and degradation. Economic growth and development excuses government in many developing countries in Asia, South America and Africa to convert and exploit the forest. According to Indonesian Ministry of Forestry (2011), deforestation rate in Indonesian Borneo, including all provinces in Kalimantan, reached about 333,122.2 ha in 2009-2010. The prime sources of deforestation and forest degradation in Kalimantan are timber extraction from forest concessions, plantation establishment, and weak government supervision and control (Curran et al., 1999).

1.1.1. Tropical forest of East and North Kalimantan

Since 2012, East Kalimantan province was divided into two provinces: North Kalimantan and East Kalimantan. Together, these two provinces have approximately 19.69 million ha of administrative land. As much as 14.65 million ha of this landmass which is equivalent to 74.4% of total land area is allotted for forest (Indonesian Ministry of Forestry, 2011).

In line with the national forest grand design based on the expected function, forest area in each provinces and districts are also classified into production forest, protection forest or conservation forest. According to the Indonesian Ministry of Forestry (2011), from 14.65 million ha of allotted forest in East and North Kalimantan, about 9.73 million ha is allocated for production forest mainly for timber. Starting from 1960's, this production forest area has been licensed to hundreds of forest concessions. The number of forest concessions in East Kalimantan fluctuated in the last 30 years but up to 2012, there are 83 active forest concessions for natural timber production in East and North Kalimantan forest (Indonesian Ministry of Forestry, 2012).

In general, East and North Kalimantan forest has rapidly changed in the last 40 years. First problems emerged from logging itself. Logging activities which include tree felling and skidding damaged the residual stand and a large proportion of the remaining vegetation were killed (FAO, 2002). Topsoil was also removed by skidding operation and increased erosion. Sist et al. (1998) and Lynch and Talbott (1995) mentioned that uncontrolled harvesting including over-harvesting are among few of the causes of deforestation. In most cases, the excessive logging has altered species composition and stand structure significantly (FAO, 2002).

The other important cause for the decline of forest in Kalimantan is fire. First major forest fire event occurred in 1982/1983 when 3.5 million ha of East Kalimantan forest were diminished. Similar event repeated in relatively constant period of between 4-5 years but in 1997/1998 another major fire event had burnt approximately 5 million ha of East Kalimantan forest (Boer, 2002) and 80% were incinerated logged-over forest area (Lennertz and Panzer, 1983 cited by Boer, 2002). Another root of deforestation in this province is forest encroachment which involving intricate social problems. When government failed to accommodate local people interest and recognizing their rights, conflicts ignited. Forest encroachment cases also involves migrant from which they open forest to another land use (mostly agricultural land) to get fortune from road access inside the forest. The situation has worsened when Suharto regime fall in 1998. Transition has driven national attention to politics and economics reform while law enforcement was weakened.

Another major driving factor of deforestation in East and North Kalimantan is the conversion of natural forest to monoculture forest by planting fast growing species (plantation forest) such as *Acacia* sp. or *Eucalyptus* sp. In addition, deforestation issue in these provinces also involves mining concession. East and North Kalimantan are sources of coal which attracted people and business corporations to exploit it. In addition to coal, mining of ore and minerals also contributed for deforestation. In Indonesia, these minerals are classified as strategic natural resources according to regulation. In case of these resources were found beneath forest area, the government will give extra priority to exploit it rather than conserve the forest.

When plantation forest is allowed to establish only in the forest areas, oil palm (*Elaeis guineensis*) plantations - another booming monoculture plantation - starts to invade non-forest areas. Koh and Wilcove (2008) revealed that as much as 56% of oil palm plantation in Indonesia may be grown up now from the conversion of primary, secondary or plantation forest land as origin. Non-forest area is the area which is allocated for supporting non-forestry project and development such as expansion of agricultural land, settlement and transmigration areas, crops estates, etc., including oil palm plantation. The authority in charge to manage these non-forest area is given to local government either district or provincial government. Non-forest area in East Kalimantan does not always means a typical bare land, grass land, bushes or other type of non-vegetated land but in fact in some areas it was still covered by even dense forest. Once oil palm estate granted to these areas, what happens next is the massive clear cutting. All trees except a few species such as honey tree (*Koompassia excelsa*) will be cut down, removed, burnt (in some cases, land clearing by fire is still widely practiced although it is prohibited by law) and replaced by oil palm trees. High demand of oil palm land from foreign and local investors make everything worsen. Recently, district government in East Kalimantan tried to ask more non-forest area allocation to the central government in Jakarta using investment issues as a bargain. If the request is approved, forest becomes more suppressed.

1.1.2. The need for sustainable forest management in Indonesia

Term of sustainability is basically a concept which emphasize on the relation of the continuity of human society and nature. The principles of sustainability are intended for guiding human activities towards a secure future, for controlling dynamic of living systems (Vehkamaki, 2005). History noted that sustainability concept was a very classic idea which introduced for the first time about 3 centuries ago by Hans Carl von Carlowitz from Freiberg, Germany who published a book called "Sylvicultura Oeconomica" in 1713. The book itself talks about the guidance for the cultivation of native wild trees (Grober, n.d.) and many believed it was the first closed-related literature talking about sustainability of forest utilization as a natural resources.

Further, in that book the concept of sustainability has addressed three dimensions which are the backbone for contemporary usage of sustainability, i.e. economic, social and ecological aspect. The book also promoted the idea to control the cutting volume in order to save trees for next cutting period. The basic information on forest was advice to be obtained through forest mensuration (Vehkamaki, 2005). The concept was developed in the following years as tools and advanced calculation methods were discovered.

While the classic sustainability of forest resources mainly focused on the timber production as main objective, the modern concept brought broader and equal issues on the conservation as well as social aspect. Especially in tropical forest where forest situation are completely different compared to the boreal forest for instance. Problem due to conflict of interest to this resources need to be reconciled and it is not an easy task. Therefore, timber exploitation should be formulated in a way to minimize environment destruction, preventing biodiversity losses and improve people livelihood at the same time (Nurtjahjawilasa et al., 2013).

For most of the tropical countries, forest is one of the national income sources. In case of Indonesia, forest has been utilized by exploiting it to produce mainly timber. In order to manage this vital resource, government of Indonesia committed to implement a sustainable forest management throughout the country area after independence. Delayed by years of struggling with internal conflicts and separatism, as well as interior political instability as an impact of global polarization to western (liberal) or eastern (socialism) block, the forestry act was finally released on 1967 followed by other technical regulation and guidelines. The new act regulated not only for the sustainability of timber production but also for wildlife conservation but in relatively small portion.

After the issuance of forestry act, forest concession concept was officially adopted and timber industrialization was initiated. The forest concession (later known as *Hak Pengusahaan Hutan* or HPH) has several obligation including submitting forest planning documents and conducting forest inventory for determining harvesting volume. Selective cutting was designated as the main sylviculture regime of natural timber forest production which regulated only mature trees with dbh over 50 cm are allowed to be cut down except for *Ramin* (*Gonystylus bancanus*) and *Eboni* (*Diospyros celebica*) trees which can be harvest from dbh 35 cm. In the areas where the average of slope gradient is more than 40%, the cutting limit starts from the tree above 60 cm dbh.

The negative impact of industrialization on the environments including from tropical forest exploitation became global concern in 1960's. Scientist urged to respect ecosystem and protect environment. These efforts bore fruit when first United Nations Conference on the Human Environment was held in Stockholm, Sweden, in 1972. The conference came up with declaration of 19 principles for addressing environmental issues. The peak was remarked by the Earth Summit in Rio de Janeiro in 1992 where all country leaders around the world agreed and adopted "Agenda 21" as a blueprint for the protection of earth with sustainable development (United Nations, n.d.).

The terminology of sustainable development was introduced by Brundtland in her report to World Commission on Environment and Development in 1987. Despite of debate and critics since the report released to public (Daly, 1990; Lele, 1991), Brundtland defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Redclift, 2005). One of the critics came from the ambiguous concept of sustainable development which is often interchangeably with ecologically sustainable concept or even sometimes interpreted as "sustained growth" or "sustained change" (Lele, 1991). The principles of ecologically sustainable are based on the idea that harvest rates should equal to regeneration rates and waste emission rates should equal to the natural assimilative capacities of the ecosystem into which the wastes are emitted (Daly, 1990).

Following many international consensus, the International Tropical Timber Organization (ITTO) promoted the guidelines for sustainable management of natural tropical forests in 1992 which emphasized their 59 country members to implement the guidelines through ITTO projects. In the revised guidelines, sustainable forest management (SFM) was defined as "the process of managing forest to achieve one or more clearly specified objectives of management with regard to the production of a continuous flow of desired forest products and services without undue reduction of its inherent values and future productivity and without undue undesirable effects on the physical and social environment" (ITTO, 2005).

In 1993, Indonesia formally ratified the guidelines to be implemented at the forest concession level through decree of Ministry of Forestry No. 252/Kpts-II/1993. It clearly implies that the need for implementation of SFM is basically part of Indonesia's commitment to the international community for supporting sustainable development around the globe where Indonesia's participation is part of global solutions. The SFM is global issue where each country or nation should be participated following international corporation network.

1.1.3. Indonesia's new forest inventory guideline: an opportunity

Forest inventory is a process for obtaining information on the quality and quantity of forest resources and forms the foundation of forest planning and forest policy (Kohl et al., 2006). In addition, Meng et al. (2009) stated that forest inventory aimed to provide information for understanding the dynamics of forest to manage it in sustainable way. Indonesian government has specific policy on forest inventory through government decree No. 44/2004. According to that regulation, forest inventory are tied with different scale and objectives. The broader scale is national forest inventory, and then regional forest inventory, watershed forest inventory and at the lowest level is inventory at forest management unit (i.e. forest concession).

At forest concession level, yield regulation is the most substantial outcome from forest inventory and one of the fundamental aspects to achieve sustainability of timber-based forest management. Forest inventory data are primarily used to estimate timber standing stock of commercial trees. This estimation is then used to determine the annual allowable cut (AAC) which will guide forest manager to undertake the logging operation in their concession for one cycling period. From business point of view, this AAC information will help management to predict the cost and revenue as well as for calculating tax and retribution to the authority as obligation.

Timber forest inventory also known as timber cruising in Indonesia and has specific objective to collect information on timber potency in a certain forest area for logging plan (Forestry Department of the Republic of Indonesia, 1997). To estimate total standing stock over a new forest concession, a forest inventory with sampling intensity 0.3% need to be undertaken as prerequisite for preparing a long term 20-years of forest management planning. The forest inventory is carried out by following systematic line transect method as it regulated by the Indonesian Ministry of Forestry (Hinrichs, 1998). This forest inventory system has been practiced for nearly 4 decades. The information from the transects are simply to answer the questions on how many stems of commercial trees are available per ha and how many cubic meter (m^3) they are per ha. It does not have additional important information such as where are the locations of high tree density and so on. In addition, there was no stem volume distribution map produced since GPS (global positioning system) was not involved yet. All areas in one forest concession were assumed to have equal stem number and stem volume per ha.

However, after several decades of forest exploitation, forest may have changed both in quality and quantity. As reported by Cannon et al. (1998), logging at lowland Dipterocarp forest removed 43% of overall basal area, reducing tree density and number of species by 41% and 31%, respectively. Since forest conditions are subject to change through times, a periodic forest monitoring becomes highly necessary. The monitoring frequency should be concise to attribute with dynamics of forest and its environment situation. Therefore in 2007, Ministry of Forestry started to implement a new forest inventory design for forest concession level that will be repeated once for every 10 years (Indonesian Ministry of Forestry, 2009). It still adopted a systematic sampling plot but replaced transect sample with individual sample plot. A rectangular 20x125 m of sample plots are required to be established in the field with interval 1,000 m fixed to east-west direction. For south-north direction, the interval will vary depending on the size of the concession. The central element in this new forest inventory design is that each forest compartment should have at least one sample plot representation.

Given the variation of particular data attributes (e.g. stem volume) and degree of precision, classical statistics may compute the approximate number of sample plots by using the following formula:

$$n = \left(\frac{CV\%}{SE\%} \times t \right)^2 \quad \text{...(1.1)}$$

where *n* is number of sample plots; CV is coefficient of variation of stem volume within sample plots; SE is sampling error (desired precision) and *t* is critical value of 95% confidence interval at certain degree of freedom value. The degree of freedom value has close tied to sampling size (Kohl et al. 2006). In the new forest inventory guideline, stem volume variation (CV) among sample plots in Kalimantan was set to be 65% based on empirical data from large scale production forest area. The sampling error (SE) was maintained at level of 5%. Degree of freedom sets to infinity (∞) to incorporate with hundreds of sample plots. Therefore, the *t* value is equal to 1.96 ≅ 2 for infinitive degree of freedom.

From above statistical assumptions, number of sample plots that appropriate to represent the regional condition of Kalimantan forest is 676. However, since forest concession size is vary (ranging from less than 10,000 ha to more than 100,000 ha) from one to another; number of sample plots was not fixed to 676 to all concession. Small forest concession will have lesser sample plots compared to larger one. The most important issue is that one forest compartment[1] needs at least one sample plot representation. In the new inventory guideline, the minimum number of sample plots of forest concession with different size is given. For example forest concession with less than 10,000 ha size only need to establish 200 sample plots. Those who have concession size between 40,000 ha and 50,000 ha should have 600 sample plots while 1,200 sample plots are required for concession with more than 100,000 ha area (maximum concession size).

[1] Forest compartment definition by FAO (1998) is a permanent, geographically recognisable unit of forest land forming the basis for planning, prescription, implementation, monitoring and recording of forest operations (approximately 100 ha size in most of natural timber forest concession in Indonesia)

The most advanced and significant feature of the new forest inventory guideline is the integration of sample plot location into global positioning system (GPS). The systematic sample plot distribution is designed on the geographic information system (GIS) environment prior to forest inventory. The sample plot coordinates are then stored to the handheld GPS receiver and used by inventory crew to navigate sample plot location. In the level of forest concession, this approach altered how forest managers or forest practitioners handle the data from forest inventory. Old forest inventory system only provided non-spatial data. In order to derive desired information such as stem volume per ha or number of stem per ha, classical statistics were primarily used.

1.2. Relevance

Integrating sample plot position with GPS brought opportunity to derive spatial distribution of various forest attributes. The availability of spatial distribution map may help forest managers to set a plan of various activities such as harvesting and forest enrichment program. Spatial interpolation technique is one possible approach to derive such information. On the other hand, combination of sample plot data and remote sensing as predictor may also produce similar information of forest attributes.

In addition, forest attributes estimation can also be derived using geostatistical approach. Geostatistics is the statistical method which dealing with spatial data. It has been used widely to estimate an attribute data at particular unknown location from existing observed point location. In the context of forest inventory data, this method might be promising to produce spatial distribution of a forest attribute from sample plot data. Goestatistics is also capable of handling remote sensing data such as satellite image or digital aerial photo to estimate mean tree crown size or diameter. Once mean tree crown diameter is estimated, another forest attribute such as stem volume can be well predicted. Therefore, exploring geostatistical method to handle various recent spatial data from tropical forest of East and North Kalimantan is the main course of this study. The application of geostatistics in tropical forest of East and North

Kalimantan may bring a new window for forest managers and governments as regulator for handling and analyzing spatial data from forest.

1.3. Objectives

The main objective was to examine geostatistical method to handle various available recent spatial data attained from forest inventory or remote sensing. The outcome is expected to have contribution on the better implementation of sustainable forest management in tropical forest of East and North Kalimantan through scientific approach and widely accepted methods. The specific objectives of this study are:

1. To estimate mean tree crown diameter of mangrove and lowland Dipterocarp forest using variogram analysis of high spatial resolution remote sensing imagery
2. To estimate forest attributes such as total stem volume and aboveground biomass at forest concession scale through combination of forest inventory data, remote sensing and geostatistical approach (kriging interpolation analysis)
3. To produce site suitability map of mangrove species using kriging interpolation

1.4. Research flow

Figure 1.1 is showing the summary of background, objectives and results of this study using flow chart. Sustainable forest management is the ultimate target of timber forest management in Indonesia particularly in East and North Kalimantan provinces, and this study addressed to this goal. Sustainable forest management can be achieved through steps and series of actions which basically relies on two important things: 1) it needs reliable data either from forest inventory or remote sensing, and 2) it also needs an appropriate method for analyzing data to derive intriguing information for planning or monitoring. Such basic information includes the estimation of forest attributes such as tree crown diameter, stem volume or aboveground biomass which may help forest concession to understand their forest much better.

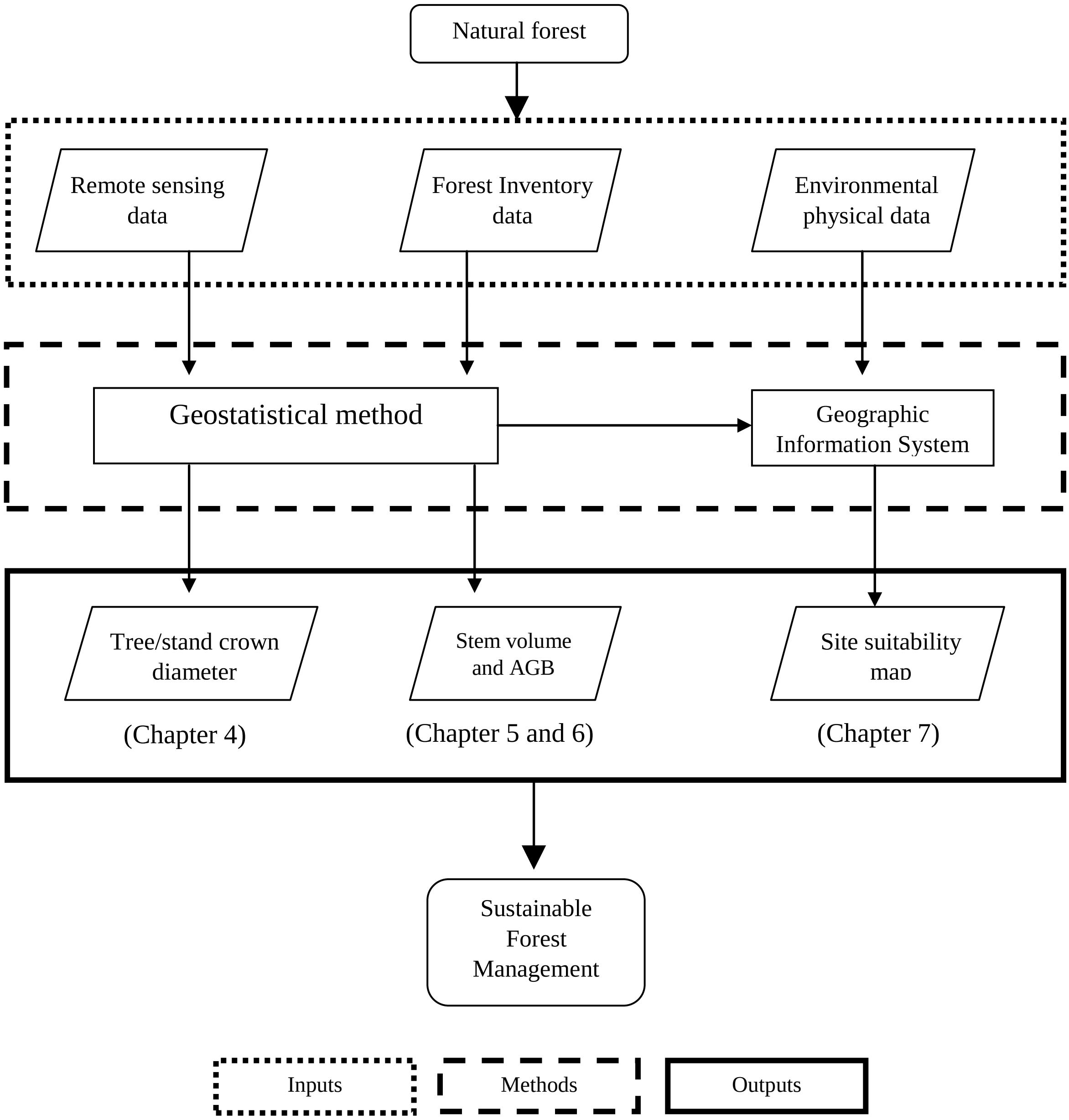

Figure 1.1. Flow chart of the study

1.5. Thesis structure

The structure of this thesis is divided into eight chapters. First Chapter discussed about the general information and current situation of tropical forest in East and North Kalimantan: problems, challenge and opportunities as well as the context, relevancy with current issues and objectives of the study. The brief concept of geostatistical method as literature review for this study is presented in Chapter 2. And the general information of each study site is given in Chapter 3.

Chapter 4 described about the application of geostatistics to estimate mean tree crown diameter in two different sites using high spatial resolution imagery. First site is mangrove forest of Mahakam delta and the second site is lowland Dipterocarp forest of PT. Batu Karang Sakti forest concession. The estimation was derived by using digital aerial photo for the mangrove site and WorldView2 satellite image for the lowland Dipterocarp site. The range of variogram was used as the predictor of mean tree crown diameter and these estimates were validated using ground measurement of crown projection from sample plots.

The estimation of basal area, stem volume and aboveground biomass (AGB) from the new forest inventory dataset of PT. Mardhika Insan Mulia forest concession is presented in Chapter 5. As many as 91 spectral-based indices and texture features of Landsat-5 TM were employed as predictors of those forest attributes constructed from sample plot data. The multi-linear regression was performed to yield a formula to estimate basal area, stem volume and AGB at pixel level. In this chapter, variogram texture features of Landsat-5 TM data was tested as forest attributes predictor.

Chapter 6 has similar objective to Chapter 5 but instead of using Landsat-5 TM data, different spatial interpolation techniques were tested. Kriging interpolation technique was explored to produce spatial distribution of stem volume of PT. Karya Lestari concession, together with inverse distance weighted (IDW) and natural neighbor. Some parameters of kriging interpolation such as mathematical models and number of neighbors were tested in order to get better estimation.

In Chapter 7, kriging interpolation technique was used to develop a site suitability map of 14 mangrove species in Mahakam delta. The site suitability map is intended to be guidance for forest rehabilitation program in this area, so that one knows which species of mangrove should be planted at a certain location. The mapping was carried out based on the mangrove site preferences table from Indonesian Ministry of Forestry which identified the preferences of 14 mangrove species to four environmental parameters, which are clay fraction, sand fraction, salinity and the frequency of tidal inundation.

Chapter 8 is the general discussion of significant findings from the previous chapters. Discussions related to these findings are also presented including some important notes to be shared as conclusions and includes recommendation for further studies.

Chapter II.

Overview on Geostatistical method

2.1. A brief concept

The concept of geostatistics was initially formulated in response to the problem in mining field which could not be solved by applying classical statistical approach. It was introduced by Georges François Paul Marie Matheron in 1963 who stated that geostatistics came along with the mining itself. For mining engineers and mining geologist, the estimation of ore grades and ore reserves as well as the error estimation of those values is fundamental (Matheron, 1963). In another book by Matheron (1971), he elaborated a theory that he called regionalized variable. Regionalize can be defined as phenomenon that spreads in space and exhibits a certain spatial structure. While classical statistics assumes that each observation of a variable is independent and having equal variability within the observation, in contrast regionalized variable emphasized that variable might have not be independent due to spatial relationship.

For mineral study, the spatial structure is quite obvious. Coal seam or ore beneath the ground surface often follow a certain direction in 3-dimensional structure. The magnitude has width, length and depth which produce a unique pattern. To predict this pattern, most of miner analysts rely on several drill boreholes sampling of soil and rock which can be distributed randomly or systematically over an area. Classical statistics definitely can derive general estimation of coal deposits using mean value ($\overline{x}$) and access the accuracy through standard deviation. However since pattern of coal undeniably exists and has a variability in space, people or miners were then interested to know in what way the different grade of coal follow each other on the field and specially what is the dimension, mass or volume of those coal at a particular position (Matheron, 1963). These questions, in theory, could not be answered by applying classical statistics.

In addition, geostatistical analysis was developed based on spatial autocorrelation which emphasized that places close to one another tend to have similar values whilst one that area farther apart differ more on average (Webster and Oliver, 2007). In many areas of geology, soil, climate and weather, ecology, agriculture or environment science in general, the evidence of the spatial autocorrelation or spatial dependence are observable. This has attracted many scientists to explore and study the phenomena. Although two of earliest methods to describe spatial autocorrelation had been developed by Moran (Moran's I index) as well as Geary (Geary's C index), however for geologist and remote sensing analyst, geostatistics (gammavariance) is most popular (Davis, 1986 cited by Getis and Ord, 1992).

2.2. Variogram and gammavariance

Principally, regionalized variable deals with spatial distribution and well expressed using a variogram which is a curve representing the degree of continuity of the variable. Variogram plots distance (*h*) of pair observation (sample point) in abscissa with the mean value of the squared of the difference between those pair in ordinate (Matheron, 1963). In many literatures and published articles, the mean squared difference of pair of observation or sample points in geostatistics was named as variance and variogram for the graph. However, for the same purpose, some other scholars preferred to use semivariance instead of variance and semivariogram instead of variogram. Therefore, in this study the terminology of gammavariance ($\gamma_{(h)}$) proposed by Bachmaier and Backes (2011) is used to replace the interchangeable terms of variance or semivariance. And for visualization of gammavariance and the distance (*h*) in the graph, the term of variogram is used. Mathematically, the gammavariance can be calculated using the following formula:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} \left\{ z(x_i) - z(x_i + h) \right\}^2 \qquad (2.1)$$

where $\gamma(h)$ is the gammavariance value at distance interval *h*; N(*h*) is number of sample value pairs within the distance interval h; $z(x_i)$ and $z(x_i + h)$ are sample values at two points separated by the distance interval *h*. All pairs of points separated by distance *h* (lag *h*) were used to calculate the experimental variogram.

A variogram has normal pattern like curve exhibiting lower gammavariance at closer distance but gradually rising up as the distance gets longer, and at certain distance the gammavariance value levels off or become constant or flatten which indicated that spatial correlation does no longer exist after that distance. Matheron (1963) mentioned that variogram is an increasing function of distance *h*. The farther two samples are one from the other, the more different they are. Figure 2.1 shows the most common variogram pattern or type. It was constructed using six point samples hence 15 possible pairs of sample were obtained. Each pairs has their own gammavariance value and distance (red dot). Plotting all 15 pairs into 2-dimensional graph, a normal variogram will emerge and display like in figure 2.1.

Using raster format data (e.g. remote sensing image), variogram may produce complex graph because of thousands or perhaps hundreds of thousands of gammavariance values were computed and displayed altogether in the graph. A complex variogram graph is often difficult to interpret or model. To handle such problem, a process called binning is suggested (Chang, 2006). Binning is another word for simplification process by means of grouping gammavariance values into specific distance classes or intervals called lags. All gammavariance values that fall into certain lag will be averaged. The average gammavariance and lags are then displayed in the variogram graph. After this process, variogram graph should look simpler. The binning process in variogram is subject to study because many techniques are available and developed such as described in Chang (2006).

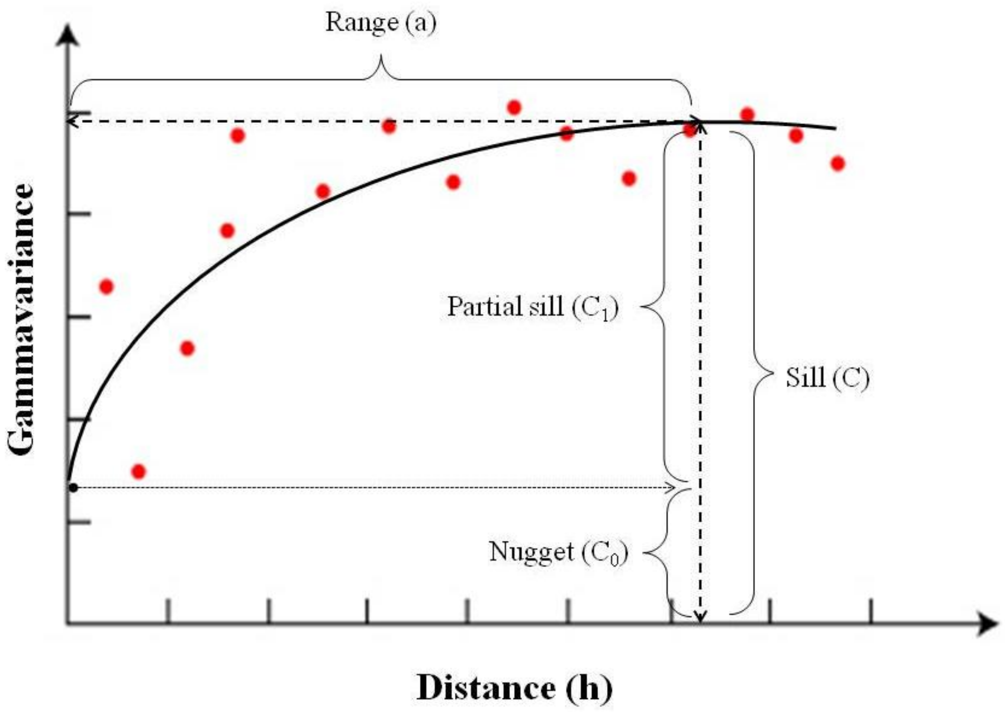

Figure 2.1. An example of a variogram graph shows the distribution of gammavariance against the distance (h). The curve line is mathematical model which further derives variogram parameters i.e. nugget, sill and range.

In order to understand the characters of variogram from different datasets, it is essential to fit a mathematical or regression model (bold curve line in figure 2.1). Some of these mathematical models such as a linear, spherical, exponential, gaussian or quadratic are often used to fit the variogram. Once a suitable model is selected, the gammavariance at any distance can be estimated. In addition, a residual also can be calculated to produce the error of estimation. Therefore, by fitting a mathematical model to variogram, the uncertainty of the estimation can be predicted.

A mathematical model has three parameters that can be used to explain the spatial correlation among dataset or sample data. These parameters are nugget, sill and range. The definition of each parameter is given by Chang (2006) as follows:

- Nugget is the gammavariance value at distance 0 (zero), representing measurement error or micro scale variation of data or both
- Sill is the gammavariance value at the point where model starts to level off or flatten

- Range is the distance at which gammavariance starts to level off or flatten. Range is also correspond to the spatially correlated portion of the data which can be used to estimate underlying object size especially when dealing with raster format data (pixel data).

In most of geostatistical studies, three mathematical models are frequently used to characterize variogram that is spherical, exponential and gaussian model. Legendre and Legendre (1998) described the standard formula to compute the models as follows:

- Spherical model: $$\gamma(h) = C_0 + C_1\left[1.5\frac{h}{a} - 0.5\left(\frac{h}{a}\right)^3\right] \text{if } h \le a$$ ....(2.2)

$$\gamma(h) = C; \text{if } h > a$$

- Exponential model: $$\gamma(h) = C_0 + C_1\left[1 - \exp\left(-3\frac{h}{a}\right)\right]$$ ....(2.3)
- Gaussian model: $$\gamma(h) = C_0 + C_1\left[1 - \exp\left(-3\frac{h^2}{a^2}\right)\right]$$ ....(2.4)

where $\gamma(h)$ is the gammavariance value at distance interval h; C_0+C_1 as well as C is basically sill, h is the distance and a is the range. The difference between these three models is presented graphically in figure 2.2.

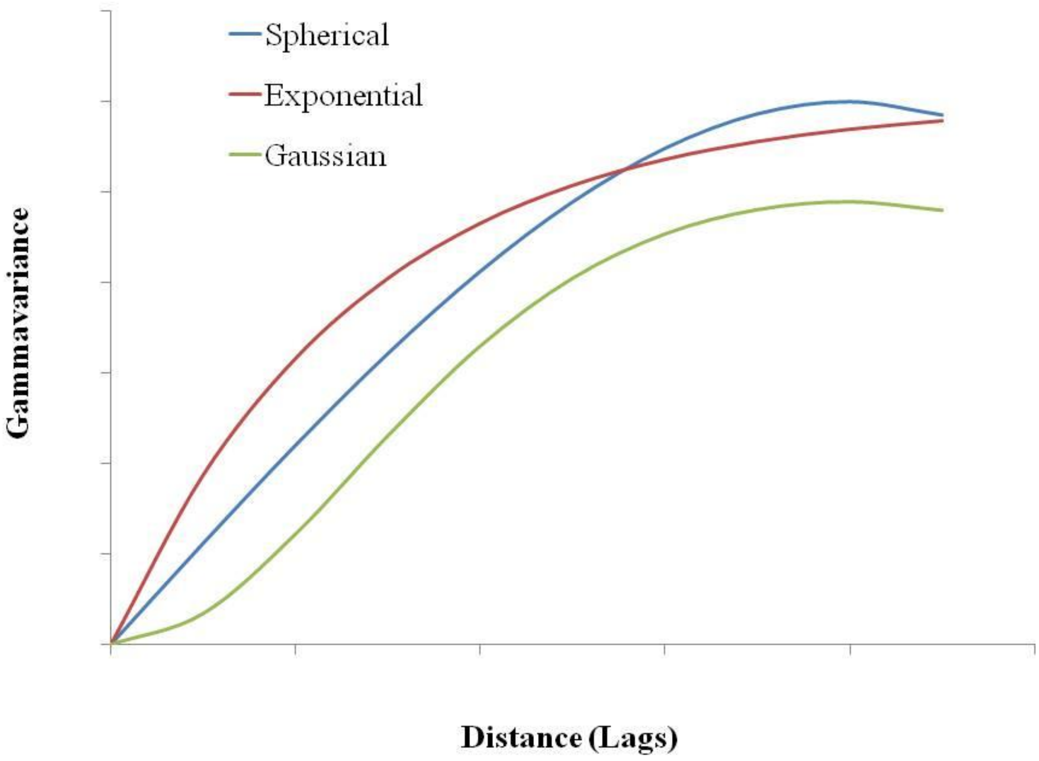

Figure 2.2. Three most common mathematical models to fit the variogram that is spherical, exponential and gaussian

2.3. Kriging interpolation

Kriging interpolation is a geostatistical-based method that has been widely used for general spatial interpolation technique. Spatial interpolation is a technique to estimate or predict value at one location by using the surrounding of known sampled values (neighbor points). The output is continuous surface layer of a variable or attribute of interest. Spatial interpolation may offer a solution of a very basic problem in the environmental studies that is insufficient of sample data. In tropical forest, low accessibility and topographical constraint are two major barriers to get enough data from the ground.

To handle this problem, spatial interpolation is a promising egress. Robinson et al. (1995) cited by Chang (2006) mentioned that spatial interpolation needs two inputs that is known points and the interpolation method. Using those inputs, spatial interpolation is basically not an isopleth mapping, which uses assigned points such as polygon centroid for point estimation. Furthermore, spatial interpolation adopts the concept of spatial autocorrelation which assumes that value estimated at a point is more influenced by nearby known points than those that are farther away (Chang, 2006).

Hence, kriging interpolation is quite different from classical statistics in a way to derive parameters of a variable such as mean or variance. Kriging relies on spatial autocorrelation concept, whereas classical methods do not (Webster and Oliver, 2007). Kriging interpolation depends on the variogram modeling. As mentioned in earlier section, the mathematical model may give the estimation of gammavariogram value at any distances. Kriging interpolation uses this mathematical model to compute the weight for each known point (the neighbor points) . Weighted process is simply manifestation of spatial autocorrelation or spatial dependency concept where closer points will get higher weight than those further apart. The following formula is mathematical term to estimate a point which comes from the sum of multiplication of known values or observed points with its weight.

$$\hat{Z}(s_0) = \sum_{i=1}^{N} \lambda_i Z(s_i) \quad \text{.......(2.5)}$$

$$\sum_{i=1}^{N} \lambda_i = 1 \quad \text{.......(2.6)}$$

where $\hat{Z}(s_0)$ is the point or location to be estimated; $Z(s_1)$ is the known point at location i and λ_i is the weight given to the $Z(s_1)$ as function of spatial dependency or autocorrelation.

Theoretically, the sum of weight is equal to one. And each of the known point most likely will have different weight. In kriging interpolation technique, the number of neighbor of known points to be incorporated in estimating the unknown point is adjustable depending on the user. Different number of neighbor results different continuous surface layer. Hence, the acquaintances on the study area are recommended to evaluate the output of kriging interpolation.

2.4. Cross-validation and assessing the uncertainty

Initial phase in applying geostatistics as mentioned in the earliest section is variogram construction and then fitting with mathematical model. In geostatistics, the validity of variogram model can be checked by comparing the estimation values and measured values through process called cross-validation (Houlding, 2000). Cross-validation works by excluding a sample (for instant sample at location A) and uses the rest of the samples to estimate the value at location A using the selected model formula. The process is repeated to other samples one by one. Since each sampled location has two values; observation value and estimation value, some of statistical parameters can be computed to evaluate the model. ESRI (2001) gives the statistical parameters as follow:

- $$ME = \frac{\sum_{i=1}^{n}\left(\hat{Z}(s_i) - z(s_i)\right)}{n} \quad (2.7)$$
- $$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(\hat{Z}(s_i) - z(s_i)\right)^2}{n}} \quad (2.8)$$
- $$ASE = \sqrt{\frac{\sum_{i=1}^{n}\hat{\sigma}(s_i)}{n}} \quad (2.9)$$
- $$MSE = \frac{\sum_{i=1}^{n}\left(\hat{Z}(s_i) - z(s_i)\right)/\hat{\sigma}(s_i)}{n} \quad (2.10)$$
- $$RMSSE = \sqrt{\frac{\sum_{i=1}^{n}\left(\hat{Z}(s_i) - z(s_i)\right)^2/\hat{\sigma}(s_i)}{n}} \quad (2.11)$$

where $\hat{Z}(s_i)$ is the predicted value from cross-validation; $z(s_i)$ is the observed value; $\hat{\sigma}(s_i)$ is the variance for location s_i and n is the number of point sample. Meanwhile, ME is mean prediction errors; RMSE is root mean square prediction errors; ASE is average kriging standard error; MSE is mean standardized prediction error and RMSSE is root mean squared standardized prediction error.

Geostatistics assumes that value at an estimated location is not really true value instead of mean value estimates from their neighbor values. In this case, statistical normal distribution is used to measure the probability of the estimated value for each location. In addition, the kriging probability distribution map can also be constructed to accompany the estimation map.

2.5. Geostatistics and geographic information system (GIS)

Geostatistics especially kriging interpolation is closely tied to geographic information system (GIS) as a system for capturing, storing, querying, analyzing and displaying geographically referenced data (Chang, 2006). GIS makes the computation faster and the outcome can be easily displayed in the computer monitor for further analysis such as visual inspection. Without computer assistant, the process will take a long time. As the computer capability increased rapidly in the last 15-20 years, and many GIS software are available at the market, variogram analysis as well as the kriging interpolation becomes easier to apply for various dataset and studies.

In this study, ArcGIS version 10.1 developed by ESRI is mainly used to perform geostatistical computation such as building variogram, model validity assessment through cross-validation process, and kriging interpolation using the extension tool called "Geostatistical Analyst". Integration of GIS and geostatistics in the same software platform is one of the advantages of ArcGIS 10.1.

2.6. Geostatistics and forestry related studies

Geostatistics was initially promoted by practical mining engineers to solve problem in the field of mining or geology where classical statistics seems unable to handle spatial autocorrelated data properly. However, the idea of geostatistics actually arose since the early 20th century and has nothing to do with mining but crops. Webster and Oliver (2007) shortly described the history of geostatistics which related to the work by Marcer and Hall published in Cambridge

Journal of Agricultural Science in 1911 who found that crop yield in the adjacent plots were more similar than those farther apart.

In relation to forestry science, a Swedish forester named Matern studied the concept of geostatistics or spatial correlation on forest. He derived a theory from random point for describing spatial covariance which later known as variogram (Webster and Oliver, 2007). Since then, the applications of geostatistics have covered various fields of researches such as petroleum, hydrology, meteorology, soil, agriculture, environment as well as forestry. It has proved to be a valuable tool in many natural resource and environmental studies (Kohl and Gertner, 1997).

Forest and geostatistics has been studied both in temperate and tropical forest. Those studies, however, were not always focused on the stand or trees but also included forest environment such as soil (Gonzales and Zak, 1994) and terrain. Feng et al. (2010) studied the range of variogram model parameter to estimate crown diameter of *Pinus* tree in China both for natural and plantation stand. Meanwhile, Song et al. (2010) used another parameter of variogram model which is sill ratio. Both studies confirms that geostatistics especially variogram analysis succeeded to estimate mean tree/stand crown diameter using high spatial resolution imagery.

Moreover, geostatistical method can also be used for modeling of environmental problem or solution. From Swiss forest damage inventory data, Kohl and Gertner (1997) succeeded to describe the spatial distribution of forest damage using two different years of forest inventory datasets. Another type of modeling by geostatistics was carried out using some indicator to obtain new information. Carroll and Pearson (1998) described on how geostatistics can be used to model butterfly species richness using tiger beetles (*Cicindelidae*) as a bio-indicator throughout North America. Advanced study on geostatistics by combining several spatial dataset (e.g. point samples and remote sensing data) has proved to increase the accuracy of kriging estimation (Castrignano et al., 2000).

Chapter III.

General information on study areas

Borneo Island is the third largest island on earth after Greenland and New Guinea. The size is about two times bigger than Japan. The island is shared by three countries; Brunei Darussalam, Malaysia and Indonesia. Approximately 72.6% of the Borneo Island belongs to Indonesia which later known as Kalimantan. Malaysia occupies 26.6% split into two states; Sabah and Sarawak, while Brunei Darussalam shares the smallest portion (less than 1%). In 1957, Indonesian government divided Kalimantan into West-, Central-, South- and East Kalimantan province. Among four provinces, East Kalimantan is the largest one with approximately 19.69 million ha and making up 10.7% of total Indonesian land.

In 2012, Indonesian government agreed to formalize a 34^{th} provincial government in Indonesia which administratively took the area of northern part of East Kalimantan. The new province encompassed 5 existing districts and city i.e. Tarakan, Bulungan, Malinau, Nunukan and Tana Tidung, and named Kalimantan Utara (literally: North Kalimantan). The total land area of North Kalimantan is now about 6.89 million ha or approximately 35% of the former East Kalimantan province before the division (figure 3.1). The transitional government is now running from its capital city of Tanjung Selor in Bulungan district. During this transitional period, data and figure of North Kalimantan still refers to its "parent province" of East Kalimantan. In this study, the official East Kalimantan data such those specific to forestry sector were used.

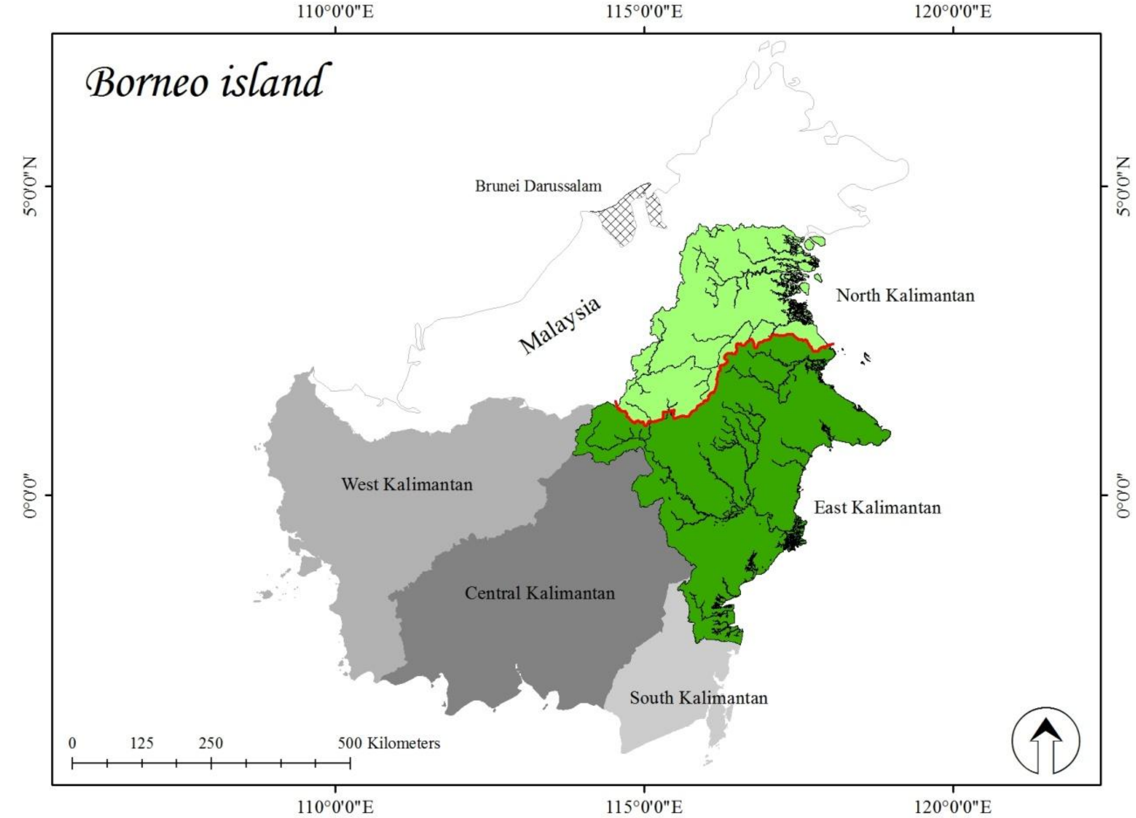

Figure 3.1. East and North Kalimantan province shares about 17.4% and 9.4% of total Borneo Island.

This study was intended to cover different type of forests in East and North Kalimantan including mangrove forest and lowland Dipterocarp forest. When study sites were selected based on the availability of spatial data such as forest inventory or remote sensing data, apparently it also covered different topographical features; from flat area of mangrove forest to rugged and hilly forest area with steep slope in the interior part of Malinau forest, now a part of North Kalimantan. Study sites comprised of three forest concessions and of mangrove forest in the Mahakam delta (figure 3.2). Although 97% of Mahakam delta is allotted for production forest but no official timber license is granted to the mangrove forest of Mahakam delta. Though no official timber exploitation, but more than 50% of mangrove forest in this area had been diminished due to massive conversion to aquaculture pond.

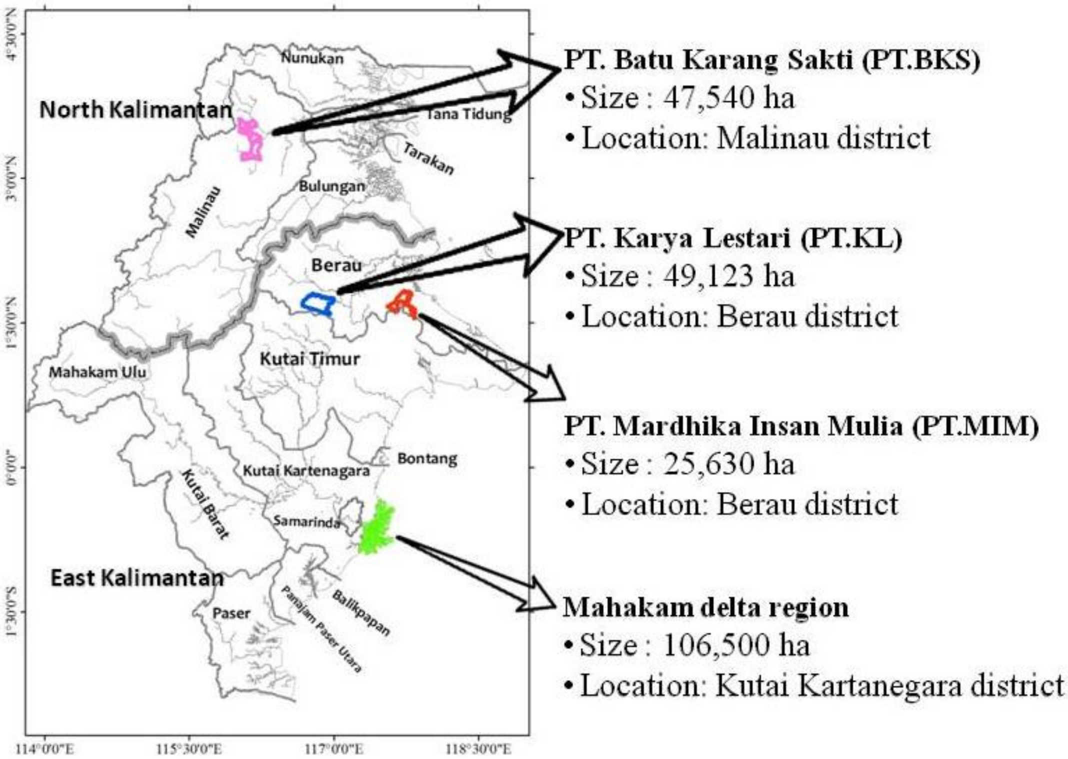

Figure 3.2. Four study sites distributed in East and North Kalimantan and covered two type of forest; lowland Dipterocarp forest and mangrove forest

3.1. PT. Batu Karang Sakti forest concession

Officially, PT. Batu Karang Sakti forest concession (PT.BKS) got the licensed for timber production in 2006, based on the Ministry of Forestry Decree No. 66/Menhut-II/2006. According to the decree, PT. BKS have the concession about 47,540 ha of natural forest in Malinau district, nowadays part of North Kalimantan province (figure 3.3). It is situated approximately 50-60 km from Malinau city to the west. PT.BKS geographically lies between 116.01^{o}-116.24^{o} East and 03.19^{o}-03.62^{o} North. The concession is crossed by two major river systems i.e. Mentarang River and Tubu River. The elevation ranges from 120-600 m above sea level and more than 50% of the area have relatively steep slope (more than 15%). From 2007 Landsat-7 ETM+ image classified by PT. BKS, about 92.7% of the total area is classified as primary forest.

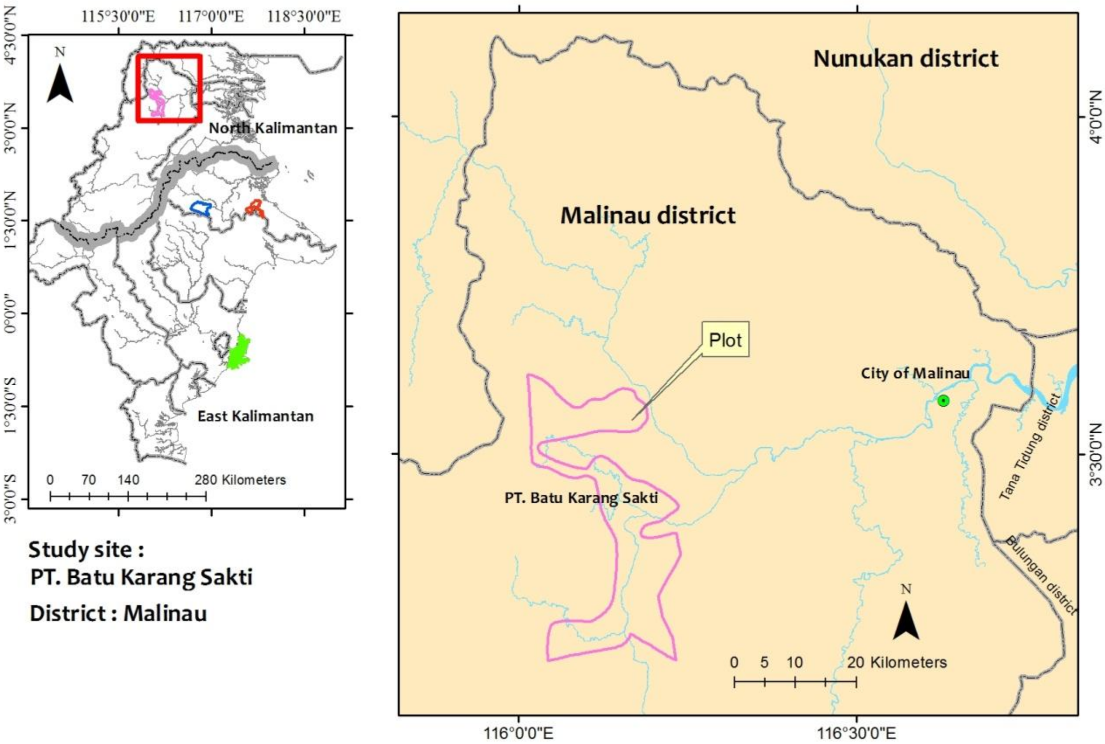

Figure 3.3. PT. Batu Karang Sakti forest concession (PT.BKS) in Malinau district, North Kalimantan. It is situated in the upper river of Mentarang and Tubu some 50-60 km from Malinau city.

3.2. PT. Karya Lestari forest concession

PT. Karya Lestari forest concession (PT.KL) is located in Berau district, now still a part of East Kalimantan. Since 1980's, Berau has been an important area for timber production because as much as 90% of Berau total land area is forest. First forest concession license in Berau was granted in 1969 and in the following years, other 14 licenses were issued, including a 330,000 ha forest concession belong to PT. Alas Helau in 1978 (Obidzinski and Barr, 2003). Since Asian economic crisis hit Indonesia in late 1990's, followed by dramatic political changed, the impact stroke in almost every aspects of Indonesian life as a nation including forestry sector. Within a few years after the crisis, many of forest concessions collapsed including PT. Alas Helau. The former area of PT. Alas Helau was then divided into several small new forest concessions and Karya Lestari forest concession was one of them.

Geographically, PT. Karya Lestari forest concession lies between 116.67°-116.99° East and 01.59°-01.80° North. They got the license in 1999 and hold about 49,123 ha of forest area based on Ministry of Forestry decree No. 846/Kpts-VI/1999. About 82% of the concession area was classified as "limited forest production" which means due to rugged topography, only trees above 60 cm of dbh are allowed to be cut down. The annual precipitation is around 2,242 mm. The elevation ranges from 63-927 m above sea level. The area with slope higher than 15% is approximately 67.1%. PT.KL is situated approximately 91 km from the capital city of Berau, Tanjung Redeb. Most of the area is logged-over forest and more than 75% of the area is covered by secondary forest (PT. Karya Lestari, 2011).

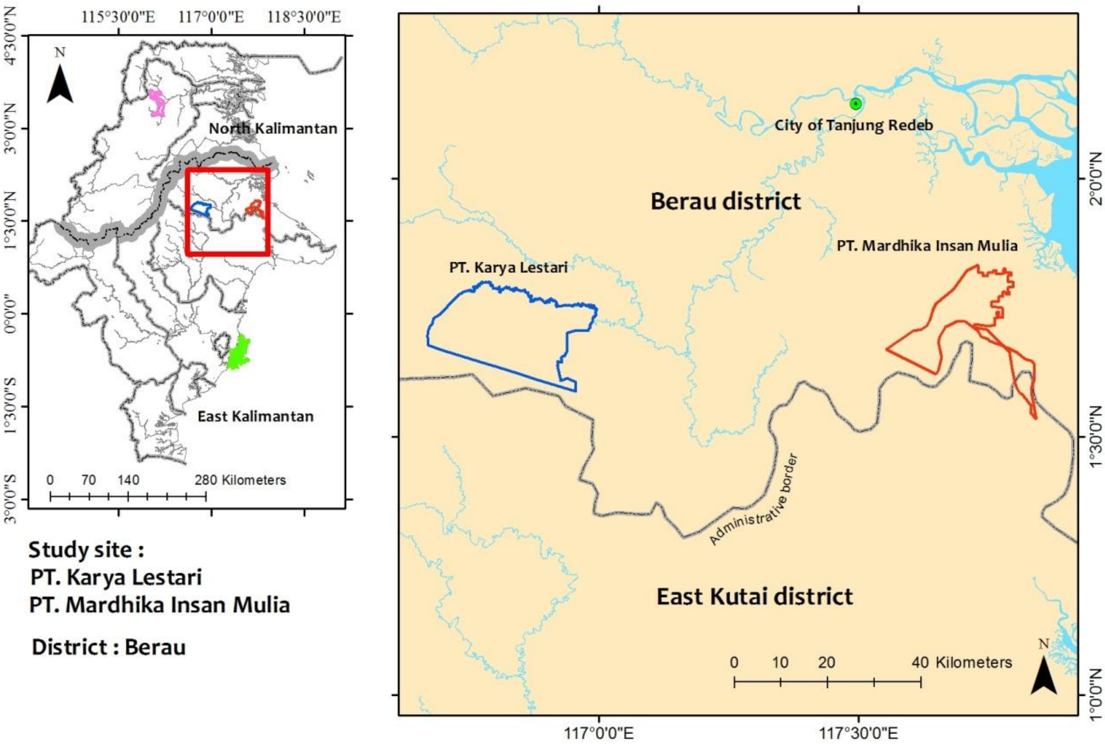

Figure 3.4. PT. Karya Lestari forest concession (PT.KL) is situated about 91 km from the city of Tanjung Redeb. Meanwhile, PT. Mardhika Insan Mulia forest concession (PT.MIM) is located only about 60 km from PT. KL. Both concessions are located at the adjacent of East Kutai district in the south.

3.3. PT. Mardhika Insan Mulia forest concession

Forest concession of PT. Mardhika Insan Mulia (PT.MIM) formerly belonged to PT. Tabalar Wood Industries. Due to some reasons, Ministry of Forestry took over the area from PT. Tabalar Wood Industries and granted it to PT. Mardhika Insan Mulia in 2008 by Ministry of Forestry decree No. 240/Menhut-II/2008. Officially, PT.MIM has the right to manage and produce timber from 25,630 ha of mainly logged-over forest. Geographically, PT. MIM forest concession lies between 117.55^o-117.85^o East and 01.54^o-01.84^o North (figure 3.4). Compared to PT.KL, the elevation in this concession is slightly lower, ranging from 26-860 m above sea level. The area with slope more than 15% is about 46.6% of the total area, relatively small compared to PT.KL and PT.BKS. According to PT. Mardhika Insan Mulia (2011), based on the interpretation of Landsat-7 ETM satellite image in 2008, about 82% or PT.MIM total area was secondary forest and leaved only 22.5% of primary forest.

In addition, as much as 87% of PT.MIM total area is classified as "limited forest production" area where only tree with dbh more than 60 cm were allowed to be cut. This forest concession lies adjacent to the protection forest in the southern part which plotted by government to preserve unique karst ecosystem. Compared to the previous forest concessions, PT.MIM has relatively better accessibility. From the capital city of Berau district, Tanjung Redeb, it takes only 2 hours by car to reach this location.

3.4. Mahakam delta region

In total, 77.3% or approximately 7.52 million ha of total production forest in East and North Kalimantan has been leased out to 129 companies or community groups. The remaining 22.7% of total production forest do not have clear management yet and that includes 99,750.5 ha of mangrove forest in Mahakam delta region (Indonesian Ministry of Forestry, 2012).

Mahakam delta region was suffered from human expansion of aquaculture land in the late 1990s. Triggered by Asian economic crisis, the shrimp product price for export was inflated due to depreciation of Indonesian currency (*Rupiah*) against US dollar (Tambunan, 2010). This situation attracted people to open mangrove and convert it to ponds. In 2001, 75% of mangrove in Mahakam delta has been degraded and most of them was removed by ponds (Zwieten et al., 2006).

Mahakam delta is located between 117.25°-117.67° East and 00.35°-01.17° South (figure 3.5). It is situated approximately 20 km from the capital city of East Kalimantan province, Samarinda. The initial ecological study by Dutrieux (1991) provided some basic information of mangrove in Mahakam delta including the vegetation. Quoting to his early findings, various mangrove species were found around the sea coast where *Avicennia* sp. predominates along with *Bruguiera gymnorhiza* and *Rhizophora* sp. to form sea-front formation. In the back, *Nypa* sp. is the dominant species.

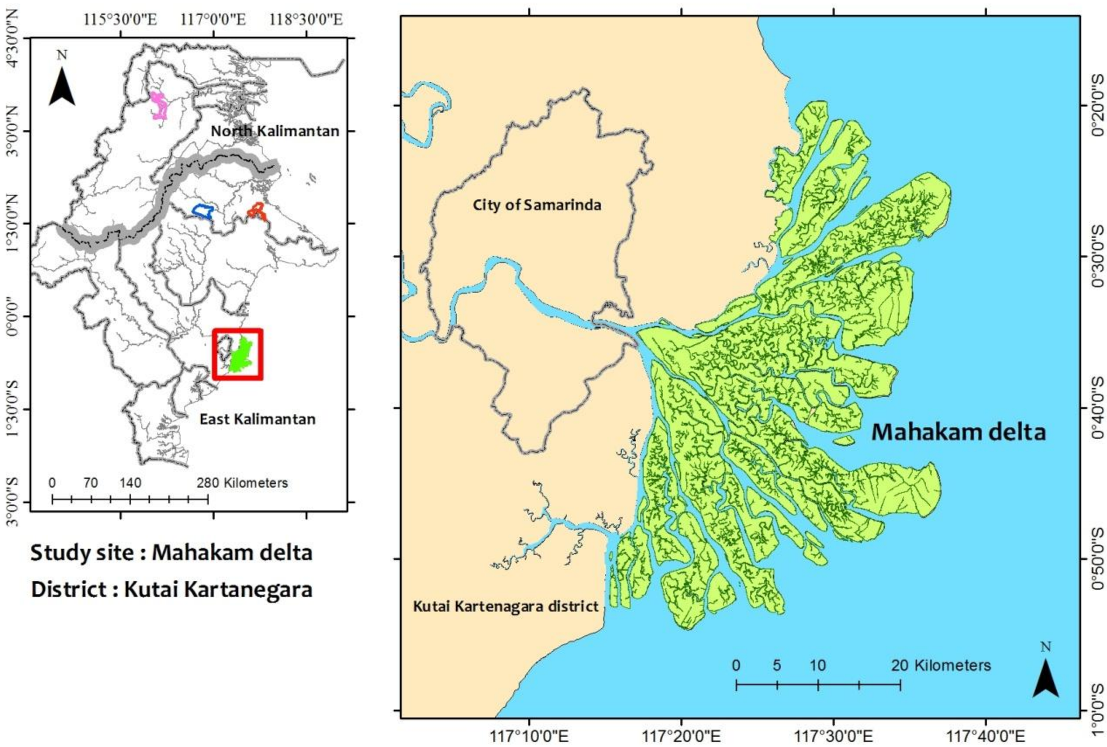

Figure 3.5. About 46 sedimentation islands forms a fan like shape of Mahakam delta in the east coast of Borneo Island.

Chapter IV. (Abridged version)

Geostatistical method for estimating mean tree crown diameter of different type of forests

4.1. Introduction

4.2. Methodology

- 4.2.1. Study area at Mahakam delta region
- 4.2.2. Study area at PT. Batu Karang Sakti forest concession
- 4.2.3. Materials
- 4.2.4. Plot establishment at Mahakam delta
- 4.2.5. Plot establishment at Batu Karang Sakti forest concession
- 4.2.6. Data preparation
- 4.2.7. Geostatistical method
- 4.2.8. Range (R_v) sensitivity test to different number of lags
- 4.2.9. Comparison of mean crown diameter from plot ($\overline{C}_d$) and mean of range ($\overline{R}_v$)

4.3. Results and discussion

- 4.3.1. Stand structure of plot data in Mahakam delta
- 4.3.2. Stand structure of plot data in PT. Batu Karang Sakti
- 4.3.3. Crown size estimation from mangrove plot
- 4.3.4. Crown size estimation from PT. Batu Karang Sakti
- 4.3.5. Diameter at breast height (dbh) and crown diameter relationship
- 4.3.6. Variogram with various number of lags for mangrove plots
- 4.3.7. Variogram with various number of lags for lowland Dipterocarp forest plots

4.4. Conclusion

This chapter is schedule to be submitted at one of the international peer review journal in the next near future. Any inquiry or further question, please send an email to suhardiman94@gmail.com

Chapter V. (Abridged version)

Estimating the attributes from East Kalimantan tropical forest using Landsat spectral and texture-based image analysis

This chapter is schedule to be submitted at one of the international peer review journal in the next near future. Any inquiry or further question, please send an email to suhardiman94@gmail.com

Chapter VI. (Abridged version)

Applying spatial interpolation techniques for stem volume estimation at forest concession scale

This chapter is schedule to be submitted at one of the international peer review journal in the next near future. Any inquiry or further question, please send an email to suhardiman94@gmail.com

Chapter VII. (Abridged version)

Geostatistics for site suitability mapping of degraded mangrove forest in the Mahakam delta

This chapter was joint authorship and has been published in :

Journal of Geographic Information System 5(5): 419-428.

Online access at http://dx.doi.org/10.4263/jgis.2013.55040.

Chapter VIII. (Abridged version)

General discussion and conclusion

8.1. General discussion

- 8.1.1. New forest inventory guideline for timber forest concession
- 8.1.2. Geostatistical method for predicting mean tree crown diameter
- 8.1.3. Geostatistical method for estimating forest attributes
- 8.1.4. Geostatistical method for environmental modeling
- 8.1.5. Geostatistics and sustainable forest management in tropics
- 8.1.6. Future study

8.2. General conclusion

- 8.2.1. Lesson learnt from this study

This chapter is general discussion from previous chapters. The content is an integral part of Chapter 4 to Chapter 8, which schedule to be submitted at one of the international peer review journal in the next near future. Any inquiry or further question, please send an email to suhardiman94@gmail.com

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