EVALUATION OF TROPICAL RAINFOREST CROWN SEGMENTATION AND INDIVIDUAL TREE INVENTORY USING AIRBORNE LIDAR DATA

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DEDICATION

This Special dedication to

My beloved family members

NOR JANAH BINTI OTHMAN

AUNI SYAZWANI BINTI MOHD YUSSAINY

AUNI SYAHIRAH BINYI MOHD YUSSAINY

MUHAMMAD AMMAR BIN MOHD YUSSAINY

Thanks for your love and care.

And also to

My lecturer, staff and friends

Thank you for your guidance and support.

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ABSTRACT

Light Detection and Ranging (LiDAR) offers higher accuracy to map forest structure at horizontal and vertical scales and thus improve the forest inventory process especially in the tropical rainforest area in Sarawak. Tree structure attributes such as Canopy Height Model (CHM) or the individual tree-and-area-based information. Tropical forest with dense canopy structures always hampers the accuracy of tree location, while the existing sampling strategy is rather random and insufficient to present the areal coverage. Furthermore, the CHM segmentation has been less tested in tropical regions, and thus, no study to identify the better method to be adapted for the forest in Borneo has been found. The study area is one of the forest plots in the Bukit Hitam Nature Reserves (BHNR) of Limbang, Sarawak covering about 22 hectares. This area was chosen because the forest diversity has been recognised as one of the nature parks in Malaysia. Therefore, this study was aimed to evaluate the existing crown segmentation method for LiDAR so-called the Marker-controlled watershed segmentation on the data measurement in BHNR. The objectives were to develop allometric relation using in-situ data; to estimate the forest crown in raster- and point-based segmentation methods; and to assess the quality of extracted canopy based on comparison with in-situ data. ArcGIS and LiDAR360 were used to perform the crown segmentation. The crown delineation from segmented results were evaluated using univariate statistics and Jaccard Index (JI). Results from ArcGIS showed an under-estimation at JI=0.41 which was less than 50% from inside the reference crown, but LiDAR360 indicated JI=0.61 representing more than half of the matching segmentation. The accuracy of crown diameter produced by ArcGIS and LiDAR360 was 15.7 and 31.7 meters respectively. This study found that LiDAR360 could offer better segmentation in raster and point-based methods and the point-based segmentation has proven that the discrete point is slightly better than the raster-based output.

ABSTRAK

Pengesanan dan pengukuran cahaya (LiDAR) memberikan ketepatan yang lebih tinggi untuk memetakan struktur hutan pada skala menegak dan mendatar dan dengan itu meningkatkan proses inventori hutan terutama di kawasan hutan hujan tropika di Sarawak. Atribut struktur pokok seperti ketinggian kanopi dan taburan menegak boleh diukur dengan LiDAR dan ini selalunya dilakukan dari pemodelan ketinggian kanopi (CHM) atau maklumat individu pokok dan luas. Hutan hujan tropika dengan struktur kanopi yang padat selalunya mengganggu ketepatan lokasi pokok sedangkan strategi pensampelan sedia ada adalah secara rawak dan tidak cukup untuk menggambarkan kawasan liputan. Seterusnya segmentasi CHM tidak banyak diuji di kawasan tropika dan oleh itu, tiada kajian yang mengenal pasti kaedah yang lebih baik untuk disesuaikan dengan hutan di Borneo. Kawasan kajian adalah salah satu satu plot hutan dalam kawasan rizab semula jadi Bukit Hitam (BHNR) di Limbang, Sarawak meliputi keluasaan sebanyak 22 hektar. Kawasan ini dipilih kerana kepelbagaian hutan yang diiktiraf sebagai salah satu taman rizab semula jadi di Malaysia. Oleh itu, kajian ini bertujuan untuk menilai teknik segmentasi silara pokok sedia ada untuk pengukuran data LiDAR yang dikenali sebagai segmentasi penada kawalan garis batas di BHNR. Objektifnya adalah untuk membangunkan hubungan antara diameter silara dan tinggi pokok daripada cerapan di lapangan; untuk mengira silara pokok dalam segmentasi secara *raster* dan titik; dan untuk menilai kualiti silara terbitan yang diekstrak berdasarkan perbandingan dengan data lapangan. Sistem ArcGIS dan LiDAR360 digunakan dalam melakukan segmentasi silara pokok. Penggarisan silara pokok dari hasil segmentasi dinilai menggunakan statistik univariat dan index Jaccard (JI). Hasil dari ArcGIS menunjukkan penilaian rendah pada JI=0.41 dengan kurang dari 50% sampel berada dalam silara rujukan namun LiDAR360 menunjukkan JI=0.61 mewakili lebih dari separuh segmentasi yang bertindan. Ketepatan diameter silara yang dihasilkan oleh ArcGIS dan LiDAR360 masing-masing adalah 15.7 dan 31.7 meter. Kajian ini mendapati bahawa LiDAR360 boleh memberikan segmentasi yang lebih baik dalam kaedah *raster* dan berdasarkan titik dan segmentasi secara titik telah membuktikan bahawa hasilan dari titik diskrit lebih baik daripada hasilan berasaskan *raster*.

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LIST OF ABBREVIATIONS

ALS	-	Airborne Laser Scanning
CD	-	Crown Diameter
CHM	-	Canopy Height Model
DBH	-	Diameter Breast Height
DEM	-	Digital Elevation Model
DTM	-	Digital Terrain Model
DSM	-	Digital Surface Model
GIS	-	Geographic Information System
GPS	-	Global Positioning System
H	-	Tree Height
3D	-	Three Dimensional Form
LiDAR	-	Light Detection and Ranging
LRB	-	Limbang River Basin
LULUCF	-	Land Use and Land Use Change and Forestry
mW	-	Milliwatts
nm	-	Nanometer
IDW	-	Inverse distance weighted
RMSE	-	Root Mean Square Error
JI	-	Jaccard Index
NDVI	-	Normalised Difference Vegetation Index

LIST OF SYMBOLS

˚C	-	Degree Celsius
d	-	Distance
A_c	-	Estimated Crown Area
A_b	-	Reference Crown Measurement
n	-	Number of Samples
R	-	Correlation Coefficient
R_g	-	Crown Parameter Measured at in-Situ
R_z	-	Crown Parameter Estimated by Lidar Data

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Forest structure gives prominent effect towards ecosystem process that determine the water, nutrient and carbon emission (Shugart et al., 2010). It also affects the availability of habitat for flora and fauna species and thus being proposed as an essential biodiversity variable for monitoring global biodiversity level (Pereira et al., 2013). Forest management requires fine spatial information of forest to design sustainable strategies and mitigation from the forest degradation and deforestation in support to the UN Framework Convention on Climate Change and the Paris agreement (García et al., 2017). Major deforestation and land conversion are evident and highway development is one of the anthropogenic activities that led to it.

The idea is to improve the transportation connectivity between Sarawak, Brunei, Sabah and Kalimantan of Indonesia. The highway development requires information about the terrain and it's on ground features involved to determine the suitability at effective cost and minimum impact to environment and society. However, land conversion is a trade-off that commits to potential forest losses within the development. As a result, it is major demand to know the loss by measuring the forest in the scene and later, impact of this deforestation can be quantified. Malaysia's first- Highway Information Modelling (HIM) was developed for the Pan Borneo Highway Sarawak was recently studied by (Akob et al., 2019), In developing HIM for the Pan Borneo Highway Sarawak, all required data was captured using several methods and technologies. This included satellite imagery, ground survey data, LiDAR data, Unmanned Aerial Vehicle (UAV) imagery and Underground Detection Mapping (UDM) (Alamgir et al., 2020).

Field-based forest inventories involve physical forest structure sampling on the landscape but this method is costly, time consuming and limited to certain accessible area which is therefore difficult to sparsely capture the heterogeneity of forest structure across the landscape (Yu et al., 2010). This is no more the issue for remote sensing technology thanks to the availability of active sensor called Light Detection and Ranging (LiDAR) which is particularly sensitive to the variation of forest structure at horizontal and vertical scales. LiDAR is successfully approved to deliver forest canopy height (García et al., 2017), above ground biomass (Asner et al., 2014), leaf area index (Zhao et al., 2015) and vertical distribution of vegetation (Fieber et al., 2015). Despite the unprecedented accuracy given by airborne measurement, there is potential research line to improve the measurement quality especially for tropical rainforest area in Sarawak. Application of LiDAR to measure the forest structure is the major focus of this study.

Highway construction and improvement may lead to series of action towards forest losses, deforestation and land conversion. Decision on highway construction and design is more subject to implication on economic concerns than are the decisions in assessing the environment and deforestation impacts to the society. However, the decision has to be subjected to requirements of environmental impact studies and licensing, providing opportunity for adjusting the decisions for any potential environmental measures. Recent studies proved that strong link between transportation construction and socioeconomic development patterns (Ji et al., 2014) and the highway became the key factor to forecast the urban sprawl (Amato et al., 2016). Yet, excessive changes by these constructions resulted in series of natural and social problems nearby (Ratner et al., 2013).

With increased accessibility of current and historical earth observation data, remote sensing based technology has been widely used to monitor and map the deforestation process and impact (Aik et al., 2020). Optical satellite imageries always become the favourite to monitor the forest degradation at the larger observation area. The spatial and spectral capabilities permit potential to map the distribution of degraded forest area (How Jin Aik et al., 2021). Medium resolution has more advantage to monitor larger area but having lower probability to access single tree information on ground. High resolution optical sensors give the benefits to monitor individual tree and the information only convey the horizontal attribute and not sensitive to the variations in the vertical vegetation structure (Ioki et al., 2019) Optical measurements are subjected to low cloud cover and promising weather condition which are not the case for tropical rainforest area. LiDAR is a revolutionary remote sensing technology for vegetation mapping thanks to its laser returns capability to map the horizontal and vertical structure and determine the structure variations at higher resolution, LiDAR provides tree structure attributes such as canopy height, sub-canopy topography and vertical distribution of intercepted surfaces (Aik et al., 2020). Individual tree-based or area-based information is the common data produced by LiDAR application for forest mapping. This study focuses on the canopy surface height modelling using the LiDAR records as the main data.

Discrete LiDAR points are hardly to present the continuous form of the real forest as the points are observed at certain interval gaps and heights due to its discrete LiDAR pulse returns and scanning routines (Hamraz et al., 2017). Analyst is encouraged to convert the detrended LiDAR cloud point to raster grid of a certain resolution, lower than the raw one, with various statistics calculation of height for laser points impinging within each grid cell. The raster grid that records the upper surface of vegetation canopy is known as the canopy height model (CHM). Basically, CHM represents in 2.5-dimension where information is at a given horizontal coordinates and with only one height information. The CHM is also defined as a surface model that carries important information about the amount and spatial distribution of tree over area (Alexander et al., 2017). It is the basis for mapping individual trees and deriving others tree information such as height and crown size (Hamraz et al., 2016). The issue lays on the fact of that the discrete sample of earth surface with discontinuities information at one cell grid so that the CHM extraction is not a straightforward method (Coops et al., 2016). Basically, if the CHM is defined based on the maximum elevation of the laser point or the maximum height within the cell, it is actually give the underestimated true maximum height. Therefore, this study highlights the applicability of LiDAR observation to map the forest crown and evaluation of crown segmentation methods performance.

1.2 Problem Statements

The in-situ measurement is essential in evaluating the results of crown delineation using LiDAR data but the current practice only determines selected tree samplings in specific forest plot area. Besides, in most cases, the GPS is used to collect the tree coordinates as waypoints where the accuracy of GPS would be contaminated by the dense canopy surrounding. The planimetric accuracy of the tree location could be far poorer if low accuracy GPS was used. The tropical forest of which dense overlapping canopy, complex vertical structures and larger leaves are evidently restrict the quality of GPS observation in positioning the measured tree (Kaartinen et al., 2015;Brach et al., 2014). Good sampling strategy is needed to maximize the potential of in-situ positioning so that it could be easily compared with LiDAR cloud points. This study considers the emergent tree as the best object identifier to visually and manually assess the coordinate of any ground tree samples. The emergent tree always exceeds others adjacent tree peak where the peak is prominent and super emergent. This anticipation may complement the tedious and almost impossible routine in collecting the coordinates point in tropical forest.

Crown width and tree height are difficult to measure from ground and such limitation can be complemented by the LiDAR observation. The LiDAR data could improve the crown related inventories at the floor level and thus helping to build the allometric models. Therefore, Canopy Height Model (CHM) is typically used to model the LiDAR derived canopy measures. Despite of the fact that the CHM generation is straightforward (comparing the DSM and DEM), the segmentation from the CHM has been less tested in tropical forest study (Basuki et al., 2009). Method of CHM segmentations have been extensively tested for coniferous forests and it is questionable to be practiced to tropical forest due to the tree shapes are irregular, diverse and almost plastic (Dai et al., 2018;Mcroberts et al., 2015). Even few methods were tested in some tropical forests area, there is no study to identify the method to adapt for forest in Borneo (Nordin et al., 2019). In fact, the focus was about the tree mapping and less on the crown segmentation (Rozali et al., 2020).

Treetop detection provides potential coordinates of individual trees based on CHM value at the location of the treetops and this is applicable for high dense point clouds over meter square. As the irregular treetops height, multi storey canopy layers and wet canopy, it is therefore difficult to extract crown size individually using typical CHM result (Nordin et al., 2019). For higher altitude LiDAR observation, point cloud density can go down to 1 point per square meter, which has lower probability to represent the actual treetop (Wästlund et al., 2018).

LiDAR provides higher quality information about the physical tree structure and permits observation to the area which is difficult to access. Operational survey routine strongly relies on the LiDAR measurement as an alternative record for inaccessible area. Forest inventory in tropical forest is always a challenging tasks in which higher accuracy of sample position in term of planimetric accuracy is needed (Brearley et al., 2019). Operative routine for forest inventory in Sarawak has been conducted for 45 years and the major acquisition variant is using ground sampling. Remote sensing based inventory was merely applied for mapping and specifically for selected area. As a result nor significant observation was considered through LiDAR due to economical and data processing constrains. In fact the forest inventory setup for Peninsular Malaysia and in the state of Sabah and Sarawak is less unified in methodology and objectives (FAO, 2007). Due to higher density canopy cover and overlapping by nearby canopy with rigorous understorey vegetation, the position of tree is misleading. Yet, it may give an issue to determine the quality and accuracy of that LiDAR derived products and this requires operator to perform ground survey collectively.

1.3 Research Questions

This study reflects to the following research questions;

(a) What is the performance of CHM segmentation for tropical forest?

(b) What is the quantitative dimension of LiDAR raster data that completely determines the forest crown?

(c) How accurate is the LiDAR derived vegetation canopy and reliable is the result towards forest losses estimation?

(d) What is the difference between raster- and point-based segmentation methods?

1.4 Aim and Objectives

This study aims to evaluate the quality of crown segmentation methods on high resolution discrete LiDAR over the Sarawak forest area. Therefore, the following objectives of this study are anticipated.

(a) To develop model relationship between crown and height from in-situ sampling.

(b) To estimate the forest crown using different raster and point-based segmentation methods.

(c) To assess the quality of extracted canopy size based on the comparison with in-situ and high-resolution airborne imageries.

1.5 Study Area

The study was conducted at Bukit Hitam Nature Reserves (BHNR) which is situated in Limbang, Division of Sarawak about 6 km from Limbang City (Figure 1.1). BHNR had gazetted on 20th April 2000 and had been recognised as one of the Nature Park in Sarawak, Malaysia that covered 22 hectares from a total area of 147 hectares, located N latitudes 4°43'04.3" and E longitudes 114°59'46.4". BHNR was also a water catchment area for Limbang town. It was preserved as a nature reserve by the Sarawak Forest Department and opened to the public for recreation and tourism activities. In 2020, Sarawak Forestry Department had recorded a total of 9,518 species of wood and non-wood forest plants which was later documented in Botanical Research and Herbarium Management System (BRAHMS). In Sarawak, there are a total of 246 species of Dipterocarp including 73 species of Dipterocarp that was found in Limbang Division in North Sarawak (SFD,2020). Flora types such as Koompassia excelsa (Tapang), Anisoptera costata (Mersawa Kesat) , Shorea leprosula Miq. (Meranti Tembaga), Hopea latifolia (Luis Daun Bulat) , Vatica odorata (Resak Ranting Kesat) and others are spotted. However, there is neither any specific information nor recorded reports about the dominant species as well as the other flora diversity in Bukit Hitam Nature Reserve, Limbang since it was the first LiDAR study that had been conducted in the particular area. In addition, there are two rivers spotted in BHNR namely Payan River and Wassai Hitam River. Limbang River flows a distance of 196 km before it discharges into the South China Sea, at Brunei Bay. The Limbang River Basin (LRB) exhibits varied terrain characteristics and highly undulating nature with an elevation ranging from sea level to 2,400 m above mean sea level. The majority of the LRB were covered with primary and secondary forests (more than 90%) but also included oil palm plantations and mixed agriculture.

Malaysia’s climate can be characterized by three main components namely wind pattern, rain fall and temperature. In addition, the presence of El-Nino Southern Oscillation (ENSO), Indian Ocean Dipole (IOD) periodic cycle and Madden Julian Oscillation (MJO) affects Malaysia's rainfall distribution (JMT,2019). As for Sarawak, this state received rainfall of various amounts throughout the year in two monsoon seasons, which determined the climatic conditions of the study area. The monsoon seasons in this region last from May to September (Southwest Monsoon) and from November to March (Northeast Monsoon) but these are separated within two short inter-monsoon months i.e. April and October. The Northeast monsoon is the wettest period and the Southwest monsoon comparatively drier (DID, 2015). The study area (LRB) receives an annual average rainfall of 3,851 mm with monthly mean rainfall exceeding 250 mm. Due to the high amount of rainfall and the peculiar relief characteristics of the research site, lower areas in the LRB experience repeated severe flash flooding during the peak monsoon seasons. The average daily temperature ranges from 25℃ to 35℃ during the day and 18℃ to 21℃ at night with the humidity varying from 70 to 90 percent (Hua et al., 2013). The major human development activity in the study region was timber harvesting, which altered the terrain conditions and induced severe soil erosion during heavy rainfall as well as affecting the climatic conditions of this region (Vijith et al., 2018).

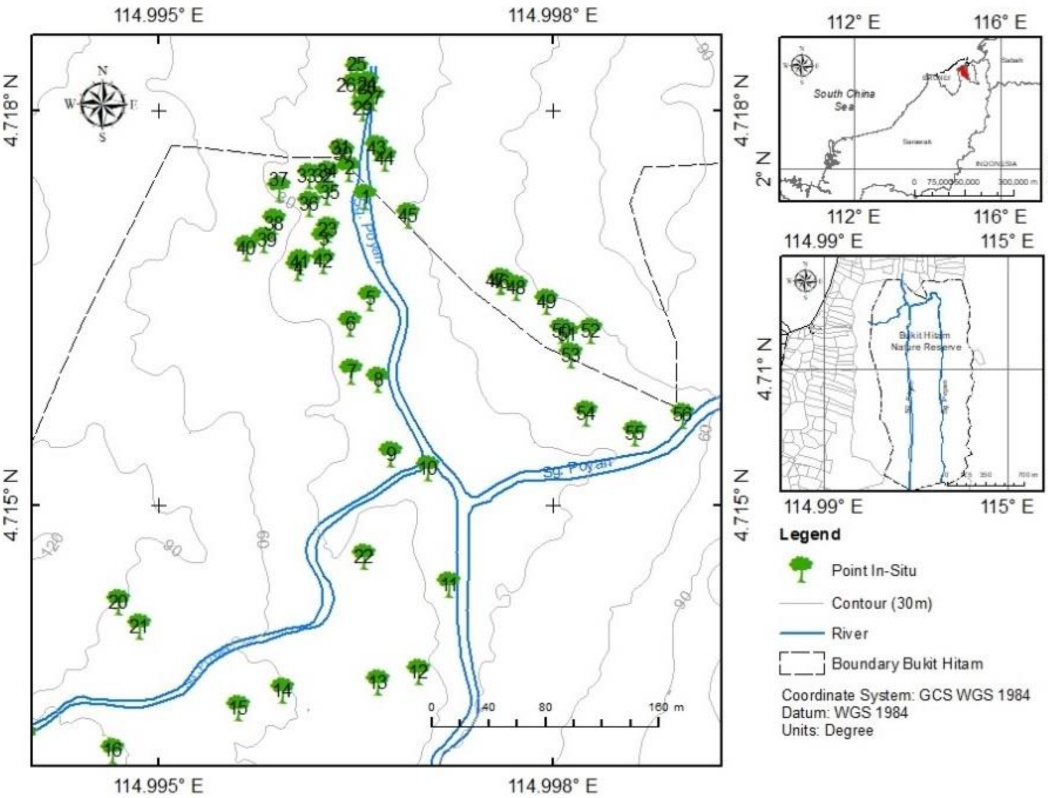

Figure 1.1 Map of Bukit Hitam Bukit Hitam Nature Reserves (BHNR)

1.6 Scope of the Study

The scope of this study lies on the following topics;

(a) Discrete pulse LiDAR data

Only discrete pulse LiDAR data is considered instead of the continuous wave-form information available during the measurement. The first and the last pulse returns are used for canopy measurement as other pulse returns (2nd, 3rd or 4th) were neglected. Thus, no below canopy structure is investigated as most of the second and third returns have lower signal-to-noise ratio (SNR) (below 10dB) which imply larger random error. The LiDAR data within the buffer of 600 meter from the centre line of propose highway is considered.

(b) Associated orthoimage

Orthoimage simultaneously acquired with LiDAR is used for data processing. This image covers the same area by LiDAR points. It is the by-product and no further processing is anticipated as the image quality is preserved. The aerial photo was validated by the vendor at accuracy of below 30 cm based on the ground control points established during the flight mission and observation.

(c) In-situ measurement setup

In-situ data was collected by identify the emergent trees on the ground. 56 samples was recorded by using GPS handheld. The GPS handheld was the only tool recommended by the practical surveyor to be used in this study for positioning inside the Bukit Hitam Nature Reserve (BHNR) with expected accuracy of 6 – 10 meters (at minimum GPS communication with satellites). The coordinates of the tree is hypothetically represent only the position of the emergent tree. Although there is ForestGeo Lambir (52-ha Long-Term Ecological Research plot) adjacently located, the LiDAR observation was not covered and passing the area. Yet the study assumes similar forest diversity in both BHNR and ForestGeo Lambir areas. Visible and independent small trees below 30 cm DBH were chosen manual ground control emergent tree.

1.7 Significance of the Study

LiDAR was proven to be useful tool in forestry especially in height characterization of the tree structure and also the forest landscapes (Kelly et al., 2015). By using the integration of digital optical camera, the horizontal canopy crown information is effectively captured. Studies showed that various efforts had been done in studying the crown morphology using these two variables (Jing et al., 2014).

Crown width and tree height are difficult to measure in the tropical rainforest from ground and such limitation can be complimented by LiDAR observation. This study is to provide the methodology framework to evaluate the performance and reliability of the forest inventory measurements in the tropical rainforest. Tree canopy mapping is relevant for individual tree isolation and thus tree structure information extraction. Such information has potential implication for forest regeneration, reducing manual fieldwork required for forest inventory and assessing the deforestation damage. In the case of Pan Borneo development, related tree inventory and particular terrain topographic information are crucial to provide higher accuracy possible. Both records significantly support the state or national forest inventory (NFI) and Environmental Impact Assessment (EIA) initiative in the Pan Borneo operation which is typically relied on the massive and tedious manual observation routines and sparse plot samples.

Information on tree canopy is pertinent to assess the forest and cropland losses that are potentially evident in changing the land cover and use into the bigger highway networks of Pan Borneo. Land conversion has great impact to the economy, social, urbanization and environment in the area close to the designated highway. By having the LiDAR derived tree canopy map, the land conversion impact can easily be estimated and then further predictive measure can be designed to sustain the ecosystem in Sarawak.

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