FOREST STRUCTURE AND ABOVE-GROUND BIOMASS ESTIMATION IN DANUM VALLEY USING AIRBORNE AIRBORNE LIDAR DATA

HUE SU WAH

THESIS SUBMITTED IN FULFILLMENT FOR THE DEGREE OF MASTER OF SCIENCE

FACULTY OF SCIENCE AND NATURAL RESOURCES
UNIVERSITI MALAYSIA SABAH
2017

UNIVERSITI MALAYSIA SABAH

BORANG PENGESAHAN STATUS TESIS

JUDUL : **FOREST STRUCTURE AND ABOVE-GROUND BIOMASS ESTIMATION IN DANUM VALLEY USING AIRBORNE LIDAR DATA**

IJAZAH : **MASTER OF SCIENCE (FORESTRY)**

Saya **HUE SU WAH,** Sesi **2016 – 2017,** mengaku membenarkan tesis Sarjana ini disimpan di Perpustakaan Universiti Malaysia Sabah dengan syarat – syarat kegunaan seperti berikut:

1. Tesis ini adalah hak milik Universiti Malaysia Sabah.
2. Perpustakaan Universiti Malaysia Sabah dibenarkan membuat salinan untuk tujuan pengajian sahaja.
3. Perpustakaan dibenarkan membuat salinan tesis ini sebagai bahan pertukaran antara institusi pengajian tinggi.
4. Sila tandakan (/):

[ ]	SULIT	(Mengandungi maklumat yang berdarjah keselamatan atau kepentingan Malaysia seperti yang termaktub di dalam AKTA RAHSIA 1972)
[ ]	TERHAD	(Mengandungi maklumat TERHAD yang telah ditentukan oleh organisasi/badan di mana penyelidikan dijalankan)
[/]	TIDAK TERHAD	

Disahkan Oleh,

HUE SU WAH
MF1311002T

(Tandatangan Pustakawan)

Tarikh: 08 September 2017

(Prof. Madya. Dr. Phua Mui How)
Penyelia

DECLARATION

I hereby declare that the data and content of this thesis of masters degree was completed on my own. This study contains no material which has been accepted for the award of any institution and university except for the cited equations, summaries and references.

08 September 2017

HUE SU WAH
MF1311002T

CERTIFICATION

NAME	:	**HUE SU WAH**
MATRIC NO.	:	**MF1311002T**
TITLE	:	**FOREST STRUCTURE AND ABOVE-GROUND CARBON STOCK ESTIMATION IN DANUM VALLEY USING AIRBORNE LIDAR DATA**
DEGREE	:	**MASTER OF SCIENCE (FORESTRY)**
VIVA DATE	:	**6 JUNE 2017**

CERTIFIED BY;

Signature

1. **SUPERVISOR**
Assoc. Prof. Dr. Phua Mui How

ACKNOWLEDGEMENTS

It is my genuine pleasure to express my gratitude to my supervisor Prof.Dr.Phua Mui How for his dedication and scientific approach. He have helped his student in a great extent to improve our study. His timely advise with kindness and dynamism have help me to complete my study. I also like to express my appreciation to Dr.Keiko Ioki for her advice on every stage of my study. Besides, I would like to take this opportinuty to thank Dr.Wilson Wong and Mr.Alex Korom for their guide and advise throughout the study.

I am extremely thankful to all the staffs of Royal Society in Danum Valley Centre for their kind help and co-operation throughout my data collection, especially to the research assistant Deddie and Azzlin. It is my privilege to thank my friend Daniel James for his constant support and advise throughout my study. This study was completed with hard work in the field with Nik Firdaus, Rozaidi, Ahmad Dasuki and Shazrul Azwan which I am deeply appreciated. My appreciation extends to my family and friends that supported me especially to Ling Zia Yiing, Chong Chee Wei, Cassandra Chong Yii Wen, Chua Cheok Shan, Melissa Sharmah Gilbert, Sitti Suraidah Binti Anas and Grace Singan. I would like to thank to my friends Linda, Ferra and Florina that involved in the same project.

Hue Su Wah

08 September 2017

ABSTRACT

Above-ground Biomass (AGB) estimation in tropical forest is challenging due to the complex forest structure. Evolving technology in remote sensing especially *airborne Light Detection and Ranging* (LiDAR) is a promising technology that construct a three dimensional model of the complex forest canopy. The application of airborne LiDAR data was examined to estimate AGB of the primary and the logged over forest near to Danum Valley Conservation Area (DVCA). Field based AGB was calculated using the allometric equations of Yamakura (Yamakura *et al.* 1986) and Chave (Chave *et al.*, 2014). A total of 50 plots were collected in the primary (n=20) and logged-over (n=30) forests. The structure of the forests were analyzed using the airborne LiDAR data acquired in October 2013. LiDAR metrics were calculated from the first and last returns of the point clouds at plot level to generate the height metrics and laser penetration (LPs). From the result of the stepwise regression analysis, maximum DBH was explained by a multivariate model with height metric H70 as predictor (R^2 = 0.62, RMSE = 16.59 cm). A single predictor model with height metric H90 was effective to estimate maximum tree height (R^2 = 0.88, RMSE = 3.6 m) for both forests combined while a multivariate model comprised of H10, H70 and H90 explained 87% of the Lorey's Height (LH) of the combined forest. For AGB estimation, a stepwise multiple regression analysis was used to develop an AGB model by relating the height metrics and LPs. Natural log transformation model of AGB (Chave) for both forests combined improved the AGB estimation with R^2 of 0.70 ($RMSE_{cv}$=26.16%). The predictors Hmean, LP0, LP1 and LP14 were selected in this regression model. The results suggest that airborne LiDAR is a reliable and accurate technology to estimate AGB in tropical forest in Sabah.

ABSTRAK

ANGGARAN BIOJISIM ATAS TANAH DI LEMBAH DANUM MENGGUNAKAN DATA LIDAR BAWAAN UDARA

Penganggaran biojisim atas tanah (AGB) di hutan tropika adalah sangat mencabar kerana mempunyai profil struktur hutan yang kompleks. Penggunaan teknologi penderiaan jauh terutamanya airborne Light Detection and Ranging (LiDAR) adalah teknologi yang berkesan dalam membina model tiga dimensi untuk kanopi hutan yang kompleks. Penggunaan LiDAR udara diperiksa dalam kajian ini untuk menganggarkan biojisim atas tanah (AGB) bagi hutan primer dan hutan telah dibalak yang terletak di kawasan berdekatan dengan kawasan Lembah Danum (DVCA). AGB di lapangan telah dikira dengan menggunakan persamaan alometrik daripada Yamakura et al. (1986) dan Chave et al., (2014). Sejumlah 50 plot telah dibuat di dalam hutan primer (n=20) dan hutan bekas dibalak (n=30). Struktur hutan daripada plot kawasan kajian dianalisis dan dikaitkan dengan metrik LiDAR yang telah diperolehi masa Oktober 2013. Metrik LiDAR dikira menggunakan pulangan titik laser pertama dan terakhir di peringkat plot untuk menjana metrik ketinggian LiDAR dan kadar penembusan laser (LP). Berdasarkan keputusan yang diperolehi daripada analisis regresi, DBH maksima telah dijelaskan daripada model multivariate dengan menggunakan peramal metrik ketinggian H70 (R^2 = 0.62, RMSE = 16.59cm). Model peramal yang tunggal dengan Metrik ketinggian H90 sangat efektif untuk menganggarkan ketinggian maksima pokok (R^2 = 0.88) bagi gabungan hutan primer bersama hutan bekas dibalak manakala H10, H70 and H90 menjelaskan 87% adalah daripada ketinggian Lorey (LH) di kawasan kajian. Untuk anggaran AGB, analisis regresi berganda digunakan untuk membina model ramalan AGB yang menghubungkaitkan metrik ketinggian LiDAR dan LPs. Model transformasi Logaritma asli (LN) dengan alometrik Chave meningkatkan kuasa ramanalan AGB denagan R^2 = 0.70 ($RMSE_{CV}$ = 26.16%) untuk gabungan hutan primer dengan hutan yang telah dibalak. Peramal Hmean, LP0, LP1, dan LP 14 telah dipilih dalam model analisis regresi tersebut. Keputusan menunjukkan bahawa LiDAR bawaan udara adalah teknologi yang boleh dipercayai dan tepat untuk menganggarkan AGB di dalam hutan tropika utama di Sabah.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AGB	-	Above-ground Biomass
AIC	-	Akaike Information Criterion
ALTM	-	Airborne Laser Terrain Mapper
ALOS PALSAR	-	Advanced Land Observation Satellite Phased Array type L-band Synthetic Aperture Radar
AVHRR	-	Advanced Very High Resolution Radiometer
CH	-	Centroid Height
CHP	-	Canopy height profile
CL	-	Commercial Logging
COP 11	-	Conference of Parties 11
COP 19	-	Conference of Parties 19
COP 21	-	Conference of Parties 21
CV	-	Coefficient of Variation
DBH	-	Diameter Breast Height
DBM_D	-	Dry Biomass
DEM	-	Digital Elevation Model
DGPS	-	Differential Global Positioning System
DMC_D	-	Dry Matter Content
DVCA	-	Danum Valley Conservation Area
DVCF	-	Danum Valley Field Center
DTM	-	Digital Terrain Model
ENSO	-	El Nino- Southern Oscillation
ERS	-	Europe Remote Sensing
EM	-	Electromagnetic Wavelength
FAO	-	Food and Agriculture Organization
FBM_D	-	Aboveground fresh Biomass
FREL_S	-	Forest Reference Emission Level
FRL_S	-	Forest Reference Levels
GHG	-	Greenhouse Gasses

GNSS	-	Global Navigation Satellite System
GLONASS	-	Global Orbiting Navigation Satellite System
GPS	-	Global Positioning System
GRDN	-	Ground return ratio
HOME	-	Height of Median Energy
HRPM	-	Heading, Roll, Pitch, Mirror Scale
HTRT	-	Height/median ratio
IAKAR	-	Inertially-Aided Kinematic Ambiguity Resolution
IPCC	-	Intergovernmental Panel on Climate Change
INS	-	Inertial Navigation System
JUPEM	-	Malaysian department of Survey and Mapping
ITTO	-	International Timber Tropical Timber Organization
LiDAR	-	Airborne Light Detection and Ranging
LMS	-	Lidar Mapping Suit
LH	-	Lorey's height
LHT	-	LiDAR canopy height
LOOCV	-	Leave one out cross-validation
LP	-	Laser Penetration
LVIS	-	Laser Vegetation Imaging Sensor
MidIR	-	Mid-Infrared band
MODIS	-	Moderate Resolution Imaging Spectrometer
MRV	-	Measurement, Reporting and Verification
NDVI	-	Normalized Difference Vegetation Index
NIR	-	Near-Infrared
NOAA	-	National Oceanic and Atmospheric Administration
OLS	-	Ordinary Least Square
PDOP	-	Position Dilution of Precision
PLS	-	Partial Least Square
POS	-	Position and Orientation System
PRF	-	Pulse Repetitive Frequency
Procrusters R	-	Dimensional shape analysis
QMCH	-	Quadratic Mean Canopy Profile Height

REDD+	-	Reducing Emission from Deforestation and forest degradation
RIL	-	Reduced Impact Logging
RINEX	-	Receiver Independent Exchange Format
RMSE	-	Root Mean Squared Error
$RMSE_{CV}$	-	Cross Validated Root Mean Squared Error
SAR	-	Synthetic Aperture Radar
SBET	-	Smoothed Best Estimate of Trajectory
SD	-	Standard Deviation
SOC	-	Soil Organic Carbon
SOI	-	Southern Oscillation Index
SR	-	Simple ratio
SSTI	-	Sea Surface Temperature Anomalies
SWIR	-	Short Wavelength Infra-Red
SLICER	-	Slicer LiDAR Imager of Canopies by Echo Recovery
SUR	-	Seemingly Unrelated Regression
TH	-	Tree Height
TIN	-	Triangulated Irregular Networks
W_S	-	Stem Dry Weight
W_B	-	Branch Dry Weight
W_L	-	Leaf Dry Weight
UNFCCC	-	United Nations Framework Convention on Climate Change

LIST OF SYMBOLS

-	-	Minus/ dash
%	-	Percentage
.las	-	LiDAR data exchange file
'	-	Minute
"	-	Second
+	-	Plus/ positive
<	-	Less Than
=	-	Equal to
3D	-	Three Dimensional
Adj-R^2	-	Adjusted Coefficient of Determination
cm	-	Centimeter
CO_2	-	Carbon Dioxide gas
dz	-	Delta Elevation
EXP	-	Exponential
g/cm^{-3}	-	Gram per centimetre cubic
ha	-	Hectare
h_{median}	-	LiDAR height median
h_{max}	-	LiDAR maximum percentile height
h_{mean}	-	LiDAR mean percentile height
Hz	-	Hertz
kHz	-	Kilohertz
km	-	Kilometer
kts	-	Knots
Ln	-	Natural Logarithm
LP		Laser Penetration rate
m	-	Meter
m/s		Meter per second
N	-	North
n	-	Number of samples/plots/observation

N.A	-	Not Available
o	-	Degree
^oC	-	Degree Celcius
PPM^2	-	Point per square meter
PRF	-	Point repetitive frequency
R^2	-	Coefficient of determination
S.D	-	Standard deviation
S.E	-	Standard Error
Sig.	-	Significant
t/ha	-	Metric ton per hectare
×	-	Multiply
ρ		Wood Specific Gravity

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

Increasing anthropogenic pressure on the tropical rainforest in recent decades received a great attention from various parties due to the issues of global climate change. Tropical forest covers an extensive area of the equatorial region with 1770 million hectares (Mha) recorded in Global Forest Resource Assessment (FRA) of 2015 (FAO 2015, Sloan and Sayer 2015), making it as an important carbon sink and source in global carbon sequestration. Above-ground biomass (AGB) is classified as one of the main carbon pools (Gibbs *et al.*, 2007) with carbon fraction of 0.47 of the tree biomass (IPCC, 2006). Most of the biomass estimation studies focus on AGB because it accounts for most of the total forest biomass. Tropical forest biomass has declined to a critical condition due to anthropogenic activity. According to FAO (2015), about 5.5 Mha of tropical forests were destroyed annually between 2010 and 2015. Therefore, studies on AGB are very important to understand the carbon storage and sequestration in the tropical region under anthropogenic pressure.

Tropical rainforests of Southeast Asia with coverage 236.3 Mha represent a large carbon reservoir (Stibig *et al.*, 2014). However, continues deforestation in Southeast Asia with an annual change of 1.45 Mha during 2000 to 2010 (Stibig *et al.* 2014) enhanced the released of carbon dioxide (CO_2) into the atmosphere (Houghton *et al.*, 2005; Brown, 2002). To counterbalance the level of greenhouse gases (GHG) in the atmosphere and to resolve the global climate change issue, a framework of the United Nations Framework Convention on Climate Change (UNFCCC) was developed in 1992 (UNFCCC, 1992). Along with adopted Kyoto Protocol in 1997 to mitigate GHG emission effect, forests in developing countries were excluded from mitigation target in Kyoto protocol with the limited amount of GHG released. Nevertheless, flexibility mechanism under Kyoto Protocol provided an option of Clean Development Mechanism (CDM) for developed countries to meet their emission reduction by investing "offset project" in developing countries.

Under the framework of UNFCCC, Reducing Emission from Deforestation and forest Degradation (REDD) was proposed at the Conference of Parties 11 (COP 11) in 2005 as a mitigation strategy (UNFCCC, 2009). COP 13 at Bali in 2007 agreed on the Decision 2/CP.13 regarding to the "policy approaches and positive incentives" resulted mitigation program of Reducing Emission from Deforestation and forest Degradation and the role of conservation, sustainable forest management and enhancement of carbon stock in developing countries (REDD+). In COP21, REDD+ was included in the Paris agreement to conserve and enhance the sink and reservoirs of GHG in forested area. Implementation of REDD+ in Paris Agreement in helps to strengthen the response of the threat of climate change in global level. The main objective of Paris Agreement is to maintain the average global temperature increase less than 2°C above pre-industrial levels. Participated countries in the REDD+ mechanism established a national forest monitoring system to support "Measurement, Reporting and Verification" (MRV) under the guidance of Intergovernmental Panel on Climate Change (IPCC). Accurate estimation and monitoring of carbon stock is important for the REDD+ to commence.

Estimation and monitoring of using ground inventory can be expensive and time-consuming to produce a consistent data in global scale (Chave *et al.* 2005). In order to implement REDD+ effectively, remote sensing technology is recommended to employ with ground inventory (UNFCCC, 2009). Remote sensing technology can be used to assess the forest condition in large and inaccessible areas (Saatchi *et al.* 2007). Traditionally, AGB estimated using passive remote sensing in tropical region based on multispectral (Phua and Saito, 2003; Langner *et al.* 2012) and texture information (Lu and Batistella, 2005). There are numerous studies conducted in tropical forest using coarse and medium resolution images (Foody *et al.*, 2001; Phua and Saito, 2003; Langner *et al.*, 2012; Lu, 2005; Steininger, 2000; Tangki and Chappell, 2008) due to historical availability and extensive coverage.

Satellite images such as Landsat, SPOT, NOAA Advance Very High Resolution Radiometer (AVHRR), and Moderate Resolution Imaging Spectrometer

(MODIS) were often used in continental and global-scale studies based on the spectral responses reflected from the vegetation cover of the forest. Vegetation index such as Normalized Difference Vegetation Index (NDVI) is related to field biomass through a statistical model (Brown, 1997) in accessing the vegetation cover condition. However, the performance of forest structure and AGB estimation using passive remote sensing is generally challenging and unsatisfied due to complex forest structure, heterogeneity and dense canopy of tropical rainforest. Shadow effect from the emergent trees in mature forest often resulted data saturation in spectral bands and derived indices (Gibbs *et al.*, 2007) limited the forest structure assessment using course resolution satellite image. Very high-resolution satellite images (1 – 5 m) such as Quickbird, IKONOS and RapidEye provided additional detail texture information that can improve the saturation problem in the coarse resolution satellite image. Shape variable of trees or forest structure such as tree crown were extracted from high-resolution images to estimate AGB in tropical forest (Palace *et al.*, 2008; Phua *et al.*, 2014). Although very high-resolution satellite images able to perform well in forest structure and AGB estimation, cloud cover and haze condition in passive remote sensing remain as a hindrance in data analysis (Foody and Curran, 1994).

Synthetic Aperture Radar (SAR) imagining is independent from cloud and daylight conditions make it as a feasible way in obtaining a high-quality remote sensed data (Asner, 2011). SAR data including ALOS PALSAR and ERS is an active remote sensing that emits microwave or radar signal that penetrates clouds to obtain the vertical measurement of forest structure (Gibbs *et al.*, 2007). Availability of vertical information in radar data is more advantage compared with passive data which only provide the horizontal information of tree structure (Lu *et al.*, 2006). Correlation between P-band and L-band of SAR data with various forest structure parameters such as Diameter at Breast Height (DBH), basal area and tree height enable to provide an AGB estimation (Luckman *et al.*, 1997; Kurvonen *et al.*, 1999; Sader, 1987; Sun *et al.*, 2002). The performance of SAR on forest structure and AGB estimation determined by the penetration depth of the wavelength. The longer wavelength able to penetrate deeper into the forest canopy with the increasing backscatter range of SAR provide a more robust AGB estimation (Castro *et al.*, 2003; Dobson *et al.*, 1992; Lu, 2006; Luckman *et al.*, 1997). However, the signal of all SAR data tends to be saturated in complex forest structure and high AGB tropical forest, thus the usage of SAR data is limited in mature tropical forest (Luckman *et al.*, 1997; Mitchard *et al.*, 2009; Morel *et al.*, 2011).

In contrast to SAR data, airborne Light Detection and Ranging (LiDAR) able to overcome the saturation problem in providing a robust forest structure and AGB estimation. Airborne LiDAR is an active remote sensing that emits laser pulses from the sensor on the aircraft towards the ground surface and measured the time traveled by the return signal. Return signal reflected from the canopy surface, within canopy layer and some from the ground provides three-dimensional structure information of the forest (Dubayah and Drake, 2000; Lefsky *et al.*, 2002). Emitted laser pulses from airborne LiDAR are able to retrieve various kinds of forest structure parameters such as tree height, crown size, canopy density and crown volume (Means *et al.*, 1999, 2000; Magnussen *et al.*, 1999). These parameters retrieved from the airborne LiDAR were highly related to AGB estimation. High sampling data and precise geolocation of LiDAR data make it able to estimate AGB in multiple scales (Nasset, 2005; Reutebuch *et al.*, 2005). Although airborne LiDAR is comparatively expensive and relatively limited in geographic coverage, this technology remains the most promising approach in estimating AGB in complex and dense tropical forest.

The purpose of this study is to examine the performance of discrete airborne LiDAR to estimate the forest structure and AGB of a lowland tropical forest in Sabah, Malaysia. The relationships of LiDAR variables such as LiDAR metrics and Laser penetration with field based forest structure and AGB in the primary and secondary lowland dipterocarp forest were examined.

1.1 Statement of Problem

The alarming rate of deforestation and forest degradation in recent years highlighted the importance of biomass estimation in tropical rainforest. Tropical rainforest degradation contributed to the significant GHG emission where the deforestation accounted for one–fourth of all anthropogenic carbon emissions

(Houghton, 1999). Therefore, an estimate of biomass change in tropical forest is necessary to validate the carbon cycle model and to quantify the impact of deforestation and forest degradation on global climate change.

The Significant role of tropical rainforest in CO_2 mitigation led to development of REDD+ mechanism in developing countries to reduce carbon emission with the consistent national monitoring system (Sasaki *et al.*, 2011). According to "Warsaw Framework for REDD+" in COP 19, data and information used in estimation of anthropogenic emission and removals under REDD+ have to be transparent, consistent over time with the Forest Reference Emission Level (FRELs) and Forest Reference Levels (FRLs). Data and methodology improvements were encouraged in MRV whilst maintaining the consistency with FRELs and FRLs.

Using remote sensing combination with ground inventory data is recommended to improve the data and methodologies in MRV and to meet the requirement of IPCC guideline. Three method tiers were published under guidelines of IPCC 2003 to monitor the National Greenhouse Gas Inventories and to promote the engagement of different countries (IPCC 2003, 2006; Baker *et al.*, 2010). Different combination of tiers can be used for national reporting. In conjunction with REDD+ mechanism, Tier 3 and Tier 2 involved combination of ground inventory and remote sensing technology to reduce the uncertainty of carbon stock estimation. Thus, a combination of ground inventory and remote sensing is important to obtain an accurate AGB estimation.

There has been increasing research on the utilization of remote sensing technology in estimating forest structure and AGB in tropical forest. Spot-5 satellite images were used in the study of Castillo-Santiago *et al.* (2010) to estimate the tropical forest structure. Spectral and texture variable were used to predict the forest structural basal area, canopy height, timber volume and biomass in the forest of Mexico. Avitabile *et al.* (2016) estimated the AGB of the pan-tropical forest using 1 Km resolution multiple reference datasets of moderate-resolution imaging spectroradiometer (MODIS). The coarse resolution of the AGB map remain a hindrance to provide a transparent and accurate estimated from MRV REDD+. Therefore, airborne LiDAR used as an alternative by providing three dimensional