ABOVE-GROUND BIOMASS CHANGES ANALYSIS OF TROPICAL MONTANE FOREST IN SABAH USING MULTI-TEMPORAL AIRBORNE LIDAR DATA

LOH HO YAN

FACULTY OF TROPICAL FORESTRY
UNIVERSITI MALAYSIA SABAH
2021

ABOVE-GROUND BIOMASS CHANGES ANALYSIS OF TROPICAL MONTANE FOREST IN SABAH USING MULTI-TEMPORAL AIRBORNE LIDAR DATA

LOH HO YAN

**THESIS SUBMITTED IN FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE**

**FACULTY OF TROPICAL FORESTRY
UNIVERSITI MALAYSIA SABAH
2021**

UNIVERSITI MALAYSIA SABAH

BORANG PENGESAHAN STATUS TESIS

JUDUL : **ABOVE-GROUND BIOMASS CHANGES ANALYSIS OF TROPICAL MONTANE FOREST IN SABAH USING MULTI-TEMPORAL AIRBORNE LIDAR DATA**

IJAZAH : **SARJANA SASTERA**

BIDANG : **PERHUTANAN**

Saya **LOH HO YAN**, Sesi **2019-2020**, 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,

ANITA BINTI ARSAD
PUSTAKAWAN KANAN
UNIVERSITI MALAYSIA SABAH

Loh

LOH HO YAN
MS1811013T

(Tandatangan Pustakawan)

Tarikh : 25th November 2021

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

DECLARATION

I hereby declare that the materials in this thesis are my own except for quotations, excerpts, equations, summaries and references, which have been dully acknowledged.

29th July 2021

Loh

LOH HO YAN
MS1811013T

CERTIFICATION

NAME : **LOH HO YAN**

MATRIC NO. : **MS1811013T**

TITTLE : **ABOVE-GROUND BIOMASS CHANGES ANALYSIS OF TROPICAL MONTANE FOREST IN SABAH USING MULTI-TEMPORAL AIRBORNE LiDAR DATA**

DEGREE : **MASTER OF SCIENCE**

FIELD : **FORESTRY**

VIVA DATE : **29th July 2021**

CERTIFIED BY;

Signature

SUPERVISOR
Professor. GS. Dr. Phua Mui How

ACKNOWLEDGEMENT

First and foremost, I would like to thank the Almighty God for the wisdom, strength, peace of mind and good health he bestowed upon me in order to complete my dissertation study.

It is a genuine pleasure to express my sincere gratitude to my supervisor, Professor. GS. Dr. Phua Mui How for all his supervision, suggestion, motivation, and support throughout my master study and research. I would also like to thank him for his endless patience, tolerance and opportunity he had given me, especially when I ran into trouble for accomplishing my study. Overwhelming dedication and attitude in scholarly advice, meticulous scrutiny, and the scientific approach he gave have helped me to accomplish my study.

Secondly, I would like to thank the Ministry of Science, Technology and Innovation, Malaysia for the research grant funding (Science Fund SCF0092-SEA-2016) and also thank the Kementerian Pendidikan Tinggi for the research grant funding (FRG0521). I am grateful to Sabah Forestry Department for research permission and Sabah Forest Industries Sdn. Bhd. in particular for field supports.

Special thanks are also dedicated to Mr. Daniel James, Ms. Charissa Jasmine Wong, Mr. Jim Liew Jun Fei, Dr. Keiko Ioki, Dr. Wilson Wong Vun Chiong, Mr. Rozaidi Hassan, Mr. Ahmad Dasuki bin Hj Kopong, Mr. Erwan Silin, Mr. Seli @ Seliman bin Rajion who has helped and contributed a lot in the field data collection for my study. Further thanks to Mr. Daniel James, Ms. Charissa Jasmine Wong and Mr. Jim Liew Jun Fei who are my lab-mates, for sharing their knowledge and advice on my data analysis and helping me with important comments and thoughts on my thesis writing.

The completion of my study could not have been accomplished without the support of friends and family, especially my dearest beloved father and mother, Loh Siew Nyen and Eng Mei Cheng, who has always stood by me and giving unconditional love and support to me to complete my study.

Loh Ho Yan
29th July 2021

ABSTRACT

Depleting carbon stock in tropical forests due to deforestation and forest degradation significantly causes increasing greenhouse gases emissions into the atmosphere. Mitigating climate change with the REDD+ mechanism requires accurate estimation and monitoring of the forest carbon stock changes. This study aimed at examining above-ground biomass (AGB) changes in a tropical montane forest of Ulu Padas, Sabah, between 2012 and 2017 using multi-temporal airborne Light Detection and Ranging (LiDAR) data. Indirect (i.e., estimating the AGB at each point in time and deriving the changes as their difference) and direct (i.e., estimating the AGB changes using the differences in LiDAR-derived variables) approaches were evaluated for estimating the AGB changes. Stepwise multiple linear regressions analysis was used to select model variables in both approaches. For indirect approach, the best AGB models had the adjusted R^2 = 0.784 and adjusted R^2 = 0.809 for 2012 and 2017, respectively. Overall, the relative RMSE of the AGB changes through the indirect approach was +1.413 Mg/ha/yr or 29.80 %. The direct approach produced an AGB change model (adjusted R^2 = 0.321, RMSE = 6.37 Mg/ha/yr) with the change of 45th percentile of height (Δp45) and maximum height (Δh_{max}) as the variables. The indirect approach was clearly superior to the direct approach for estimating the AGB changes. Based on the AGB change map derived from the indirect approach, the study area had a mean annual AGB increase of 8.91 Mg/ha/yr that occurred mostly at logged over forests. The mean annual AGB decrease rate was -7.49 Mg/ha/yr, mostly found at the state-land due to the land use conversions. This study demonstrated that the AGB changes in the montane forest can be accurately quantified using multi-temporal LiDAR data with the indirect approach. LiDAR based estimation and monitoring should be applied in the implementation of REDD+ projects in tropical forests.

ABSTRAK

ANALISIS PERUBAHAN BIOJISIM ATAS TANAH DI HUTAN TROPIKA MONTANE DI SABAH MENGGUAKAN DATA LIDAR DATA MULTI-TEMPORAL

Penurunan stok karbon di hutan tropika yang disebabkan oleh penebangan hutan dan degradasi hutan mengakibatkan peningkatan pelepasan gas rumah hijau ke atmosfera. Menggurangkan perubahan iklim dengan perlaksanaan mekanisme REDD+ memerlukan anggaran dan pemantauan perubahan stok karbon hutan yang tepat. Kajian ini bertujuan untuk mengkaji perubahan biojisim atas tanah (AGB) di hutan tropika montane di Ulu Padas, Sabah, antara tahun 2012 dan 2017 dengan menggunakan data Light Detection and Ranging (LiDAR) multi-temporal. Pendekatan secara tidak langsung (iaitu, menganggar AGB pada setiap titik waktu dan memperoleh perubahan sebagai perbezaannya) dan secara langsung (iaitu, menganggar perubahan AGB dengan menggunakan perbezaan pemboleh ubah yang dari data LiDAR) telah digunnakan bagi mengangar perubahan AGB. Analisis stepwise multiple linear regression telah digunakan untuk memilih pemboleh ubah yang digunakan dalam model untuk kedua-dua pendekatan tersebut. Model AGB terbaik bagi pendekatan secara tidak langsung untuk 2012 mempunyai $R^2 = 0.784$ *dan untuk 2017 mempunyai* $R^2 = 0.809$*. Secara keseluruhan, RMSE relatif untuk perubahan AGB dari pendekatan secara tidak langsung adalah +1.413 Mg/ha/yr atau 29.80 %. Pendekatan secara langsung menghasilkan model perubahan AGB (*$R^2 = 0.321$*, RMSE = 6.37 Mg/ha/yr) dengan menggunakan dua pemboleh ubah iaitu perubahan persentil ketinggian ke-45 (Δp45) dan maksimum ketinggian (*Δh_{max}*). Pendekatan secara tidak langsung adalah lebih efektif daripada pendekatan secara langsung untuk menganggarkan perubahan AGB. Berdasarkan pada peta perubahan AGB yang terhasil daripada pendekatan secara tidak langsung, kawasan yang mempunyai purata kenaikan tahunan AGB sebanyak 8.91 Mg/ha/yr belaku kebanyakannya di kawasan penebangan. Purata kadar penurunan AGB tahunan adalah -7.49 Mg/ha/yr, kebanyakannya berlaku di kawasan kampung yang disebabkan oleh perubahan penggunaan tanah. Kajian ini menunjukkan bahawa perubahan AGB di hutan montane dapat dianggar secara tepat dengan menggunakan data LiDAR multi-temporal melalui pendekatan secara tidak langsung. Anggaran dan pemantauan menggunakan LiDAR harus diaplikasikan dalam pelaksanaan projek REDD+ di kawasan hutan tropika.*

LIST OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AGB - Above-ground biomass
a.k.a - Also known as
AVHRR - Advanced Very High Resolution Radiometer
CDM - Clean Development Mechanism
CHM - canopy height model
COP - Conference of the Parties
CO_2 - Carbon dioxide
DBH - Diameter at breast height
DEM - Digital elevation model
DSM - Digital surface model
DTM - Digital terrain model
EVI - enhanced vegetation index
GDS - Global Detection Solution (GDS) Sdn Bhd
GEDI - Global Ecosystem Dynamics Investigation
GIS - Geographic information systems
GLAS - Geoscience Laser Altimeter System
GNSS - Global Navigation Satelite System
GPS - global positioning system
GSFC - Goddard Space Flight Center
ICESat - Ice, Cloud, and Land Elevation Satellite
ICRAF - International Center for Research in Agroforestry
IMU - inertial measurement unit
IPCC - Intergovernmental Panel on Climate Change
JUPEM - Department of Survey and Mapping Malaysia
LiDAR - Light detection and ranging
LMS - Laser Mapping Suite
LOOCV - leave-one-out cross validation
LULUCF - Land use, land-use changes and forestry
LVIS - Laser Vegetation Imaging Sensor
MODIS - Moderate Resolution Imaging Spectroradiometer
MRV - Measurement, reporting, and verification

NASA	-	National Aeronautics and Space Administration
NDVI	-	normalized difference vegetation index
POSPac MMS	-	Position and Orientation System Post-processing Package Mobile Mapping Suite
PPMC	-	Pearson Product-Moment Correlation
REDD	-	Reduction of Emission from Deforestation and Forest Degradation
RMSE	-	Root mean square error
SAR	-	Synthetic Aperture Radar
SAVI	-	soil adjusted vegetation index
SFI	-	Sabah Forest Industries Sdn. Bhd.
UMS	-	Universiti Malaysia Sabah
UNFCCC	-	United Nations Framework Convention on Climate Change
3D	-	Three–dimension

LIST OF SYMBOLS

% - Percentage

= - Equal

- - Minus

+ - Plus

× - Multiply

± - Plus-minus

points/m^2 - Point per meter square

t C/ha/yr - Tonne Carbon per hectare

Gt - Gigatonnes

Mg/ha - Megagram per hectare

mm - Millimeter

cm - Centimeter

m - Meter

m^2 - Meter square

m s^{-1} - Meter per second

km - Kilometer

Hz - Hertz

KHz - Kilohertz

mrad - Milliradian

r - Correlation coefficient

R^2 - Coefficient of determination

adjusted R^2 - Adjusted coefficient of determination

e.g. - For example

- Number

° - Degree

N - North

S - South

LP - Laser penetration rate

Δ - Delta value

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background

The tropical forest is known for its rich biodiversity, with almost 300 tree species found within a 100-hectare area (Suratman, 2012). This type of forest is recognised as one of the carbon-rich ecosystems that stores a substantial amount of carbon dioxide (CO_2) (Philips and Lewis, 2014). Besides, there is at least 40 to 50 % of the total global forest carbon stock found within the tropical forest (Beer *et al.*, 2010; Pan *et al.*, 2011). The tropical forest is structurally complex across the broad forest environments, resulting in a relatively high turnover rate of carbon stock (Quesada *et al.*, 2012). In terms of carbon sequestration, the tropical forest possesses an annual sequestration rate of 1.3 Gt of carbon (Lewis *et al.*, 2009) and Grace *et al* (2014) report the tropical forest can sequester up to 1.85 Gt of carbon every year, in which 1.14 Gt C yr^{-1} in primary forest, 0.47 Gt C yr^{-1} in secondary forest and 0.24 Gt C yr^{-1} in forest plantation. Thus, the tropical forest plays an important role in the global carbon cycle.

According to the Intergovernmental Panel on Climate Change (IPCC) in the fifth assessment of climate change mitigation, forest and other land-use activities (e.g., logging and agriculture) are responsible for about 12 % of the net emission of carbon gases (IPCC, 2014). The anthropogenic activities remove or reduce the above-ground biomass of forest stands, which approximately half of the above-ground biomass is carbon, affecting the carbon sequestration of the forests. As for the tropics, the annual loss rate in the forest areas was about 5.5 million hectares in the past decade. Moreover, deforestation and forest degradation in the tropical region cause an annual gross emission of about 2.2 Gt to 2.8 Gt of carbon (Keenan *et al.*, 2015, Harris *et al.*, 2012; Achard *et al.*, 2014).

The depletion of the above-ground biomass that is caused by selective logging could be balanced by natural regeneration. However, when regenerated forests have a lower forest carbon stock compared to the carbon stock before the logging activities, resulting in the increase of net emission of carbon (IPCC, 2014). The reduction in forest carbon eventually leads to the increase of carbon dioxide concentration in the atmosphere, accelerating global climate change in recent decades. Since the 1990s, various mechanisms have been debated globally to reduce carbon emissions by reducing deforestation and forest degradation through a range of forest conservation and management activities as well as enhancing the forest carbon pool capacity.

Reduction of Emission from Deforestation and Forest Degradation (REDD) is known as a global climate change mitigation framework under the United Nations Framework Convention on Climate Change (UNFCCC). The REDD was discussed in 2005 at the 11th Conference of the Parties (COP) to reduce emission from deforestation and forest degradation in developing countries, and in 2007 at COP 13, this framework was expanded to include a range of activities of conservation, sustainable forest management and forest carbon stock enhancement. The broadened version is known as REDD-plus (REDD+) (Hirata *et al.*, 2012). The REDD+ mechanism contributes a good framework toward the global climate change problems. Implementing activities in the context of the REDD+ mechanism can increase forest carbon stock and reduce carbon footprints, resulting in the long-term reduction of forest carbon emission (Ochieng *et al.*, 2016; UNFCCC, 2014; IPCC, 2006). Based on the REDD+ mechanism, results-based payments are offered to the REDD+ member countries for a significant emissions reduction of carbon (Achard *et al.*, 2014; Ochieng *et al.*, 2016). An accurate system of measure, report, and verify (MRV) that monitors carbon changes is key to the success of REDD+. However, it is only practicable if the carbon stock changes can be accurately estimated.

In order to cater to the REDD + mechanism implementation, it is necessary to accurately quantify the above-ground biomass and it changes as an approach to understand the forest carbon pool dynamics. Advancement in remote sensing technology provides robust approaches for estimating above-ground biomass over a large area (Gleason and Im, 2011). Remote sensing technology has been considered as an effective method to estimate above-ground biomass in combination with field inventory data (Soenen *et al.*, 2010, Baccini *et al.*, 2017; Tsitsi, 2016) because this technology can delineate the Earth surface information accurately, cost-effectively, and repetitively at a different level of region coverage (Avitabile *et al.*, 2012; Soenen *et al.*, 2010; Kumar *et al.*, 2017). High-spatial resolution of remote sensing data, such as satellite images (e.g., Quickbird and Worldview), airborne laser scanning data, and unmanned aerial photography, provides detailed forest structural information for estimating above-ground biomass (Kumar *et al.*, 2016). Moreover, the high-spatial resolution datasets are able to solve and minimise data saturation problems (Tsitsi, 2016). Thus, remote sensing technology and data are needed to estimate above-ground biomass with high accuracy.

Light detection and ranging (LiDAR) is a laser-based remote sensing technology that is utilised the pulses of light to measure a target distance (Reutebuch *et al.*, 2005). Millions of pulses that are emitted and returned after hitting an object produce a three-dimension (3D) high-spatial detail model of the target area. Information such as slope, features and topography of a target area that are derived from the LiDAR data are valuable for a wide range of applications, such as in forestry and ecological applications (Melin *et al*, 2017). LiDAR has been widely applied for estimating and mapping the above-ground biomass (McRoberts *et al.*, 2013, Kumar *et al.*, 2017) because the LiDAR data provides promising forest height information and forest vertical structures (Xu *et al.*, 2017; Urbazaev *et al.*, 2018). Overall, the forest information and parameters that are derived from the LiDAR data can accurately estimate above-ground biomass and produce high-spatial resolution maps.

1.2 Problem Statement

The accurate estimate of the above-ground biomass changes is one of the crucial requirements in the “Reduction of Emission from Deforestation and Forest Degradation–plus” (REDD+) project to mitigate the greenhouse effect in developing countries, providing an informative scheme for both developed and developing countries in combating the global climate change (Kissinger *et al.*, 2012). As an effort for better monitoring the above-ground biomass in the forestry industry to improve forest governance approaches, Sabah Forestry Department has been involved in the Sabah EU–REDD + project that is funded by the European Union to contribute a sustained and low carbon development within the state. This practice is also in line with the current forestry sector development under thrust 4, objective 6 stated in the Sabah Forest Policy 2018. Therefore, it is necessary to have fine spatial details and an accurate estimated above-ground biomass map in the tropical forest.

According to the forest carbon accounting guidelines developed by Intergovernmental Panel on Climate Change (IPCC), forest biomass can estimate via three (3) tiers level, where higher tier level methods can generate more accurate results. Thus, there is necessary to estimate the above-ground biomass as well as its changes accurately using ground measurement data with a combination of the high-spatial resolution datasets in the tropical forest in Malaysia.

High-resolution airborne and spaceborne remote sensing data have been studied to estimate the above-ground biomass in the tropical forest (Phua *et al.*, 2017; Jucker *et al.,* 2018). Recent studies had proved that the forest vertical structures that are extracted from full-waveform LiDAR data are conducive to estimate above-ground biomass accurately in the tropical forest (Ioki *et al.,* 2014; Kronseder *et al.,* 2012; Bazezew *et al.,* 2018). However, there is still a lack of study in deriving high accuracy of above-ground biomass in the tropical montane forest in Sabah using a discrete-return LiDAR sensor.

The above-ground biomass change map between 2000 and 2012 in tropical montane forest was estimated using LiDAR data and SRTM-DEM (Loh *et al.*, 2020) and there is still lack of study in estimating above-ground biomass changes using multi-temporal LiDAR data. LiDAR data of the tropical montane forest in Sabah was scanned during 2012 and 2017. Therefore, provides an opportunity to estimate the above-ground biomass and its changes using the multi-temporal airborne LiDAR data.

1.3 Justification

The tropical forest is one of the main carbon sinks in the global carbon cycle. Anthropogenic activities such as deforestation and forest degradation had led to serious consequences in above-ground biomass reduction. Meanwhile, afforestation and reforestation restore the capacity of carbon sink, at the same time minimise carbon emission. These direct human-induced conversion activities put above-ground biomass in a state of flux. Therefore, it is important to estimate the above-ground biomass changes as an effort for planning the forest management strategies under the context of the REDD+ project.

Airborne LiDAR, which are the discrete-return and full-waveform sensors, can delineate more precise forest structure information that can be used to provide detailed reference data to estimate above-ground biomass, especially in remote areas. Forest canopy and its structures have beelinen using a full-waveform LiDAR sensor in the tropical regions (Ioki *et al.,* 2014; Bazezew *et al.*, 2018; Wulder *et al.*, 2008; Asner *et al.*, 2012; Coomes *et al.*, 2017). Full waveform LiDAR sensor is popular among the forestry sector due to its backscattered energy in each emitted laser pulses that are able to fully access the forest canopy (Lefsky *et al.,* 1999; Lim *et al.,* 2003; Ussyshkin *et al.,* 2010). However, studies using the discrete-return sensor to estimate above-ground biomass in the tropical montane forest were limited. Therefore, it is important to evaluate the discrete-return LiDAR sensor for characterising the forest structure and ground topography to estimate above-ground biomass in the tropical montane forest.